Amitava Rakshit
Purushothaman Chirakuzhyil Abhilash
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Adaptive Soil Management: From Theory to Practices

Springer

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Dedicated to our wives

Preface

The amount of arable land available to meet the increasing demand from burgeoning population, leading to the intensification of land use, and the use of marginal lands, including sloping land. As natural areas shrink and fragment, it is a huge challenge to sustain economic growth and conserve biological diversity and ecological integrity. New ideas are being developed, such as the provision of different soil management options according to the existing infrastructure and possibilities towards development of integrated biophysical and socio-economic approach with an emphasis on adaptive research. To meet this unprecedented challenge, adaptive management is becoming a viable alternative for wider applications towards combating nutrient depletion, managing problem soils, managing soil erosion, and optimizing soil water use. Adaptive management can be generally defined as an iterative decision-making tool which is both operationally and conceptually a simple aid that incorporates users to acknowledge and account for uncertainty, and sustain an operating environment that allows for its reduction through careful planning, evaluation, and learning until desired results are achieved. Understanding these complexities is a prerequisite to the healthy functioning of a habitable Earth by instigating our thinking process and to temper our actions reminding our responsibilities for every action performed. This multifaceted exercise requires stated management objectives to make informed decisions in order to employ appropriate actions and explicit assumptions about expected outcomes to compare against actual outcomes. The book *Adaptive Soil Management : From Theory to Practices* is going to focus in detail on learning and adapting, through partnerships of managers, scientists, and other stakeholders who learn together how to create and maintain sustainable resource systems. The book represents an up-to-date state of scientific knowledge of adaptive management, identifies the conditions in which adaptive management should be considered, and describes the process of using adaptive management for managing natural resources. Further it discusses in-depth decision support tools applying science and different simulation modeling approaches on system use efficiency at the farm level and presents a framework and conditions for adaptive decision making, and also focuses some challenges in its application. Another unique feature of this book is that all aspects of this interdisciplinary technology, where knowledge, methods, and expertise are required from natural science, geography, microbiology, soil science, agronomy, biochemical engineering, and computer science, will be discussed. In this edited book, we are going to address the issue with a holistic and systematic approach that utilizes natural resources to secure sustainable environmental, economic, and social benefits for adaptive management restoring a firm relationship between land, water, and plants are managed in ways that mimic nature.

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Finally, the production team members deserve special appreciation for guiding us through the process of publishing a new work. Last but not the least, we should thank our family, immediate and extended, who always encouraged us to continue the massive task. In spite of the best efforts, it is possible that some errors may have crept into the compilation. Each of the chapter has been the primary responsibility of the invited author/group of authors: we have also read and critiqued all the chapters with extraordinary case. We shall be highly obligated to receive constructive comments and suggestions from the readers for further improvement in the future editions.

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Part I

Concepts

Digital Soil Mapping and Best Management of Soil Resources: A Brief Discussion with Few Case Studies

1

Priyabrata Santra, Mahesh Kumar, N.R. Panwar, and B.S. Das

Abstract

Soil plays a key role in agricultural production system by supporting plant growth as well as in hydrological cycle by partitioning rainwater into runoff and infiltration. Therefore, knowledge on soil properties helps in better management of both soil and water resources for sustainable crop production. However, soils vary largely in space and therefore characterizing it for a particular landscape with a set of soil parameters is a difficult task. Often, there is need to collect multiple soil samples from a landscape for characterization purpose in order to minimize the spatial variation effect and is not always feasible. Most of the times, a homogeneous zone is assumed with similar soil properties to eliminate the variation effect. Soil mapping helps in characterizing the soil resources in a better way and recently introduced digital soil mapping approach is more appropriate for this purpose. In this approach, spatial variation of soil properties and its relation with other landscape and environment variables in the form of 'scorpan' factors are considered while mapping soil properties in a spatial domain. Mathematical models are also established between soil properties and environment variables exploiting the available legacy soil data and hugely available digital data on earth features in recent times. Hyperspectral soil signatures have also a potential role to improve the digital soil products further. In this chapter, we discuss the basics of digital soil mapping approach and its needs, semivariogram fitting, kriging and its variations, accuracy and uncertainty of digital maps, role of pedotransfer (PTF) and spectrotransfer (STF) models in digital soil mapping, future prospect of hyperspectral signatures in mapping soil properties and few cases studies on

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digital soil mapping. Finally, it is expected that digital soil maps are available in different IT platforms, e.g. internet, desktop computer, mobile apps, webGIS platform, etc., to make them useful to end users.

Keywords
Soil management • Digital soil mapping • Kriging • PTFs • Hyperspectral signature

1.1 Introduction

In recent times, there is huge improvement in data computation and information technology in all fields. Keeping in pace with this improvement, there are growing interests to apply these advanced technologies in soil science also through generating soil inference system, spatial soil information system, digital soil maps, etc., in different platforms, e.g. desktop applications, android application, web map services, etc. Efforts have been done for creation of soil database at regional, national, continental and worldwide scales for wide uses of soil information by end users. For creation of such huge database throughout the world, there is challenge to develop suitable tools and techniques involving advanced data analysis methods. Apart from it, several auxiliary information are available nowadays to improve the above said goal of developing digital soil maps or soil inference system. For example, digital elevation model (DEM), proximally sensed soil signatures from remote sensing platforms have been proved as powerful tools for improvement of digital soil products and these data are also easily available. As a consequence, merging of different allied subjects like geographic information system (GIS), remote sensing, geography, computer science, etc., with soil science has been observed. Pedometrics has gained much more attention than never before. Therefore, several efforts have been made for applying digital technologies in old soil survey concept for mapping soil resources. Soil resources are mapped by creating either class map or soil attribute map. These digital soil maps are quite different from digitized version of previously prepared soil map through soil survey where a polygon boundary represents a homogeneous soil, which has also been called us mapping unit. Recently it has been felt that digital soil mapping technique should enter into its operational phase from research phase throughout the world, which has also been visualized in different parts (Padarian et al. 2015; Jiang et al. 2016; Vaysse and Lagacherie 2014; Minasny and McBratney 2016).

For sustainable agricultural production system, rapid and reliable assessment of soil characteristics is an important step. Conventional soil resource characterization through soil sampling followed by laboratory analysis has not been always feasible for rapid assessment. Under such cases, sensing methods may be a reliable option through which several soil properties can be estimated by a single scan. During last few decades, remote sensing approaches have been proved to provide solutions for rapid soil assessment. Moreover, the advantages of remote sensing approaches are its fast and nondestructive nature as well as have large spatial coverage. Four major factors influence the remote sensing signature of soil, e.g. mineral composition, organic matter, soil moisture and texture. Earlier, remote sensing approaches have been used for different applications in soil science, e.g. soil classification, soil resources mapping, soil moisture assessment and soil degradation mapping. Particularly, hyperspectral remote sensing (HRS) has been emerged as a promising tool for rapid assessment of soil resources due to its capability to measure the reflectance of soil at several contiguous and narrow wavelength bands (Das et al. 2015). Availability of soil spectral library containing spectral information of several soil types offers an opportunity to estimate multiple soil attributes from the same reflectance spectra. Keeping in mind the progresses in applications of data mining, machine learning, GIS and hyperspectral techniques in soil science, there is huge scope of digital soil mapping for management of soil resources. Here, we discuss few basics, methodology and case studies of digital soil mapping in the following sections.

1.2 Why Soil Mapping?

In agricultural production system, soil plays a major role by supporting plant growth. Management of soil resources is essential to maintain its productivity for obtaining optimum crop yield. For best management of soil resources, knowledge on its current state is required. For example, right amount of fertilizer and manure can be applied if we know the soil fertility status and the nutrient requirement of a particular crop. Similarly, knowledge on soil water retention and hydraulic conductivity helps to apply right amount of irrigation water at right time. Even the state of soil physicochemical properties, e.g. pH, electrical conductivity, etc., helps in calculating right amount of amendments to reclaim problematic soils. Not only in agricultural production system, soils play critical role in partitioning water balance components in hydrological studies. Gathering knowledge on soil properties can be done through soil sampling followed by laboratory analysis. Since soil varies largely in space, different management practices are required for different type of soil and hence multiple samples need to be collected. However, it is difficult to measure soil properties at all possible locations within a study area and hence approximation is made by considering a homogenous zone with similar soil properties. These homogeneous zones are called as management zone or block for which similar management practices are followed, whereas these practices will be different across different zones. Therefore, people have started to delineate these management zones as polygon boundary, which is termed as mapping unit. Thus soil maps have been prepared for different purpose at different scale. Soil maps were previously mapped through field survey at large scale. At recent times, specifically with popularization of precision agriculture, soil maps are required at farm scale or even at plot scale and for this purpose advanced digital mapping techniques are being employed. In the following sections, we discuss different soil mapping techniques.

1.3 Spatial Variation and Geostatistics

Classical statistics assumes that the expected value of a soil property z at any location x within a sampling area is

$$z(x) = \mu + \varepsilon(x) \quad (1.1)$$

where μ is the population mean or expected value of z and $\varepsilon(x)$ represents a random, spatially uncorrelated dispersion of values about the mean. Deviations from the population mean are assumed to be normally distributed with a variance of σ^2. Because mean values are used for estimation of properties at unknown locations within sampling units, statistics of dispersion (e.g. coefficients of variation, standard deviation, standard error, confidence limits) are used to indicate precision of the mean as an estimator. Actually, soil properties are continuous variables whose values at any location can be expected to vary according to direction and distance of separation from neighbouring samples. It indicates that soil properties exhibit spatial dependence within some localized region. Therefore, estimation using the classical model cannot be improved unless this spatially dependent variance is considered in mapping procedures. For spatial interpolation, classical statistical model is inadequate, because it does not take into account of spatial correlation structure. For this purpose, geostatistical techniques need to be employed where regionalized variable theory is considered. In real field, each soil property behaves like regionalized variables with spatial dependencies between its values at different lag distances.

1.3.1 Regionalized Variable Theory and Geostatistics

The theory of regionalized variables takes into account both the random and structured characteristics of spatially distributed variables to provide quantitative tools for their description and optimal, unbiased estimation. Geostatistics are based on the concepts of regionalized variables, random functions and stationarity. A brief theoretical discussion of these concepts is necessary for application of geostatistical tools in spatial analysis of soil properties.

1.3.1.1 Regionalized Variable and Random Function

A random variable is a measurement of individuals that is expected to vary according to some probability distribution law (Henley 1981). The random variable is characterized by the parameters of the distribution, such as the mean and variance of the normal distribution. A regionalized variable $z(x)$ is a random variable that takes different values z according to its location x within some region (Journel and Huijbregts 1978). A regionalized variable $z(x)$ is considered as a particular realization of a random variable Z for a location x within the region. If values of $z(x)$ are considered at all locations within the region, then the regionalized variable becomes a member of an infinite set of random variables $Z(x)$ for all locations within the region. Such a set is called a random function because it associates a random variable Z with any location x (Huijbregts 1975).

1.3.1.2 Stationarity

A random function $Z(x)$ is said to be first-order stationary if its expected value is the same at all locations throughout the study region,

$$E[Z(x)] = m \tag{1.2}$$

where m is the mean of classical statistics, and

$$E[Z(x) - Z(x+h)] = 0 \tag{1.3}$$

where h is the vector of separation between sample locations.

Second-order stationarity applies if the spatial covariance $C(h)$ of each $Z(x)$ and $Z(x + h)$ pair is the same (independent of position) throughout the study region and depends only on h:

$$C(h) = E[Z(x) - m][Z(x+h) - m] \tag{1.4}$$

As h gets larger, $C(h)$ decreases and the spatial covariance decays. Stationarity of $C(h)$ implies stationarity of the sample variance s^2. The spatial covariance will approach the sample variance as the distance of separation tends to zero.

Second-order stationarity does not apply if a finite variance and covariance cannot be defined, as in the case of trend phenomena (David 1977), and a weaker form of stationarity called the intrinsic hypothesis must be assumed (Journel and Huijbregts 1978). Second-order stationarity implies the intrinsic hypothesis, but not the converse. The intrinsic hypothesis requires that for all vectors of h, the variance of the increment $Z(x) - Z(x + h)$ be finite and independent of position within the region, i.e.

$$VAR[Z(x) - Z(x+h)] = E[Z(x) - Z(x+h)]^2 = 2\gamma(h) \tag{1.5}$$

Dividing by two yields the semi-variance statistic $\gamma(h)$. The semi-variance γ depends on the vector of separation h. Ideally, γ is zero at $h = 0$, but increases as h increases. The concepts of regionalized variables and stationarity provide the theoretical basis for analysis of spatial dependence using autocorrelation or semivariograms.

1.4 What Is Digital Soil Mapping?

Digital soil mapping (DSM) is defined as ‘the creation and population of spatial soil information system by the use of field and laboratory observational methods coupled with spatial and non-spatial soil inference systems’ (McBratney et al. 2003; Lagacherie et al. 2006). Recently Minasny and McBratney (2016) nicely pointed out three main components of DSM approach as reported in Lagacherie and McBratney (2006):

1. The input in the form of observed soil data measured through different field and laboratory methods including legacy soil data, available soil maps and new additional soil samples using statistical sampling techniques
2. The process of building mathematical or statistical models relating soil observations with environmental covariates or 'scorpan' factors to create spatial and non-spatial soil inference system
3. The output in the form of spatial soil information systems including raster maps of predicted soil property and their uncertainty.

Considering the above aspects of DSM approach, Grunwald (2009) reported that quantification of soil spatial pattern can be done through digital soil mapping (DSMa) and/or digital soil modeling (DSMo) techniques, which in combination can be termed as digital soil mapping and modeling (DSMM). Therefore, DSM or DSMM can be divided into three approaches: (1) pedotransfer functions, (2) geostatistical approaches and (3) state-factor (clorpt) approaches. In the sense of soil mapping, a pedotransfer function describes a mathematical function where one soil property is predicted by other soil properties, generally easier to measure (Bouma 1980). Geostatistical approaches create spatial distribution model to interpolate soil properties from point data (Krige 1951; Matheron 1962; Webster and Oliver 2007). The 'clorpt' approach combines soil mapping work with other disciplines, e.g. GIS, Geology, Environmental Science, Botany, Ecology, Meteorology, etc., by quantifying or linking the relation of soil with environmental covariates and other factors, which was originally documented in soil formation theory by Dokuchaev (1883) and Jenny (1941). Later on, McBratney et al. (2003) modified the concept of 'clorpt' approach by including few other factors into it, which is called as 'scorpan' approach. In this approach, soil class or soil attributes can be viewed as a function of the following factors:

$$S_c \text{ or } S_a = f(s, c, o, r, p, a, n) + e$$

where S_c = Soil class, S_a = soil attribute, s = soil, other soil attributes at that point, c = climate, o = organism including anthropogenic interventions, r = relief, p = parent material, a = age, time factor and n = spatial position. Most recent works on DSM follow the 'scorpan' approach to represent the soil information system in a spatial domain.

1.5 How DSM Approach Is Different from Conventional Mapping Through Soil Survey?

In the conventional approach of soil survey, soil is mapped based on surveyor's experience and field observations along with the aid of aerial photographs, remote sensing imageries, geological maps, vegetation pattern maps, etc. (Hudson 1992). All these observations were combined to draw polygons of homogeneous soil types, which are also called as the mapping units. These mapping units may be soil series, soil sub-order associations, etc. Finally, the information on different soil properties for a particular soil type is attached with each polygon in the form of attribute table in a GIS environment. Earlier such type of maps are called as digital soil maps, which can also be called as labelled digitized polygon maps and such work was started in late 1970s (Tomlinson 1978; Bliss et al. 1995). Although these types of conventional soil maps are now available in digital format, these cannot be called as digital soil map but can be termed as digitized soil map, because no statistical models were used to quantify soil properties. However, in the DSM methodology, first a numerical model is built to quantify soil class or soil attributes using 'scorpan' approaches and then it is applied on a spatially exhaustive environmental data. Here, it is to be noted that conventional soil map prepared early can be used in the DSM approach as covariate information. It helps to identify the logic and knowledge embedded in completed surveys and exploits those in DSM approach through machine learning techniques (Moran and Bui 2002).

1.6 Methodology of Digital Soil Mapping

1.6.1 Legacy Soil Data and Covariates

Data on soil properties required for DSM are generally available as point data created through soil surveying efforts at different parts of the world, which is also called as legacy soil data. Most of these data are available for characteristic soil profiles of the region as horizon wise along with their spatial coordinates. These spatial soil databases can be converted to maps through geostatistical technique, e.g. kriging. In India, these legacy soil data are available in the form of soil series database book or detailed soil survey report created by National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Nagpur. However, it is observed that the spatial point information required for DSM at a desired scale is limited in most cases to obtain final soil maps with sufficient accuracy. Under such circumstances, spatial information on different covariates may be exploited to improve the accuracy. The potential covariates to be used in DSM approach are considered to be as factors in soil forming process as described by Jenny (1941) and later on modified as scorpan factor by McBratney et al. (2003). For example, digital elevation model (DEM) is now freely available either from SRTM data with 90 × 90 m resolution or ASTER data with 30 × 30 m, from which topography factors can be computed and used in DSM approach. Similarly land use map, spatial information on weather variables, e.g. rainfall, temperature, etc., can also be used as environmental covariates, which is also available at different scale. Apart from these, different remote sensing products are now available at very fine resolution, which can be tested to explore their correlation with soil properties and for further use in DSM approach. Overall, we can say that variety of soil data either in the form of legacy soil data or spatial soil database from experimental plots and farmers field are available at different sources, which can be converted to digital soil maps for its further utility. However, a basic requirement for converting this spatial database to map is the characterization of spatial variation of a particular soil property at the mapping scale.

1.6.2 Semivariogram Fitting

Spatial variation of soil properties can be determined through geostatistical techniques (Webster and Oliver 2007). In geostatistics, spatial variability of soil properties is expressed by semivariogram $\gamma(h)$, which measures the average dissimilarity between the data separated by a vector h (Goovaerts 1998). It is generally computed as half of the average squared difference between the components of data pairs:

$$\hat{\gamma}(h) = \frac{1}{2N(h)} \sum_{N(h)}^{i=1} [z(x_i) - z(x_i + h)]^2 \tag{1.6}$$

where $N(h)$ is the number of data pairs within a given class of distance and direction, $z(xi)$ is the value of the variable at the location xi, $z(xi + h)$ is the value of the variable at a lag of h from the location xi. Experimental semivariograms [$\gamma(h)$] as obtained from Eq. (1.6) need to be fitted in standard model to obtain three standard spatial variations parameters: nugget (C_0), sill ($C + C_0$) and range (a). Weighted least square techniques are commonly used for fitting purpose. Weights are generally assigned as inversely proportional to the number of pairs for a particular lag or the lag distance. During semivariogram calculation, maximum lag distance is generally taken as half of the minimum extent of sampling area to minimize the border effect. Best-fit model with the lowest value of residual sum of square is selected to characterize the spatial variation of that particular soil property. Following semivariogram models are commonly used to characterize the spatial variation, e.g. spherical, exponential, Gaussian and linear models.

$$\text{Spherical model}: \quad \gamma(h) = C_0 + C[1.5\frac{h}{a} - 0.5(\frac{h}{a})^3] \quad \text{if } 0 \le h \le a \ \text{ otherwise } C_0 + C \tag{1.7}$$

$$\text{Exponential model}: \quad \gamma(h) = C_0 + C_1[1 - \exp\{-\frac{h}{a}\}] \ \ for\, h \ge 0 \tag{1.8}$$

$$\text{Gaussian model}: \quad \gamma(h) = C_0 + C[1 - \exp\{\frac{-h^2}{a^2}\}] \, for\, h \ge 0 \tag{1.9}$$

$$\text{Linear model}: \quad \gamma(h) = C_0 + C_1[\frac{h}{a}] \text{if } h < a \, \text{otherwise} = C_0 + C_1 \tag{1.10}$$

In all these semivariogram models, nugget, sill and range were expressed by C_0, ($C + C_0$) and a, respectively. In case of exponential and Gaussian models, a represents the theoretical range. Practical range for these two semivariogram models is considered as the lag distance for which semivariogram value is ~95% of sill. Nugget (C_0) defines the micro-scale variability measurement error for the respective soil property, whereas partial sill (C) indicates the amount of variation which can be defined by spatial correlation structure.

1.6.3 Kriging and Its Variation

Once the spatial variation parameters are identified, estimates at unknown locations within the study area can be done through kriging technique. Ordinary kriging technique is the mostly used technique for spatial estimation of soil properties. However, different variants of OK can be used as per the data availability and their characteristics. In the following sections, different types of kriging techniques are discussed briefly.

1.6.3.1 Ordinary Kriging

Ordinary kriging estimates the value of soil attributes at unsampled locations, $z(u)$, using weighted linear combinations of known soil attributes $z(u\alpha)$ located within a neighbourhood $W(u)$ centred around u.

$$z^*(u) = \sum_{n(u)}^{\alpha=1} \lambda_\alpha z(u_\alpha) \tag{1.11}$$

where $\lambda\alpha$ is the weight assigned to datum $z(u\alpha)$ located within a given neighbourhood, $W(u)$ centred on u. Weights for n number of neighbourhood points were chosen as such so as to minimize the estimation or error variance, $\sigma_E^2(u) = \text{Var}\{z^*(u) - z(u)\}$ under the constraint of no-bias of the estimator. When the kriging predictions are made for a block instead of a point, then it is called ordinary block kriging. When the mean of the random variable to be kriged is known to us, we can incorporate this in the kriging process, which is called simple kriging. If the random variable to be kriged is highly skewed, then logarithmic transformation is done and ordinary kriging is performed over transformed variable, which is called as lognormal kriging. Here it is to be noted that proper care should be taken to back-transform the kriged output and its error. Detailed theory of these kriging techniques along with examples may be found in Webster and Oliver (2007). In all these kriging techniques, when the kriging equations are solved to obtain the weights, $\lambda\alpha$, large weights are assigned to those sampled points near to the point or block to be kriged. In general, the cumulative weights of nearest four or five points may contribute 80% of the total weight, and the next nearest ten almost all of the remainder. The weights also depend on the configuration of the sampling. The larger is the nugget variance, the smaller are the weights of the points that are nearest to target point or block. The relative weights of points also depend on the block size: as the block size increases, the weights of the nearest points decrease and those of the more distant points increase, until the weights become nearly equal. Clustered points carry less weight individually than isolated ones at the same distance.

1.6.3.2 Universal Kriging, Regression Kriging or Kriging with External Drift

Universal kriging (UK), regression kriging (RK) or kriging with external drift (KED) are sometimes considered as synonymous. All these three kriging techniques assume that spatial process of a random variable is divided into two components, one is deterministic and other is random. The first part is predicted by a deterministic trend model and second part is by ordinary kriging technique. The trend component may be predicted by auxiliary variable, data of which is available at all predicted grids. These auxiliary variables may be any landscape features, e.g. elevation, slope, land use type, etc., or environmental covariates, e.g. remote sensing signatures, rainfall pattern, etc., or even be the coordinates. When the trend part of the random variable is modeled using spatial coordinates and residual part is modeled through ordinary kriging then it is called universal kriging. Otherwise, if auxiliary environmental or landscape covariates are used to model the trend part, it is called regression kriging or kriging with external drift. The difference between RK and KED lies in the computation process. In case of RK, the trend and residual are modeled separately and output from these two steps are joined together to get the output. Whereas, in case of KED, modeling of trend and residual is done simultaneously while assigning the weights in the kriging process.

1.6.3.3 Cokriging

Cokriging is the extension of ordinary kriging of a single variable to two or more variables. There must be some coregionalization among the variables for it to be profitable. It is particularly useful if some property that can be measured cheaply at many sites is spatially correlated with one or more others that are expensive to measure and are measured at many fewer sites. It enables us to estimate the more sparsely sampled property with more precision by cokriging using the spatial information from the more intensely measured one.

1.6.3.4 Indicator Kriging and Probability Kriging

Indicator kriging is a non-linear, non-parametric form of kriging in which continuous variables are converted to binary ones (indicators). It is becoming popular because it can handle distributions of almost any kind, and empirical cumulative distributions of estimates can be computed and thereby provides confidence limits on them. It can also accommodate 'soft' qualitative information to improve prediction. Probability kriging was proposed by Sullivan (1984) because indicator kriging does not take into account the proximity of a value to the threshold, but only its position. It uses the rank order for each value, $z(x)$, normalized to 1 as the secondary variable to estimate the indicator by cokriging.

1.6.4 Accuracy and Uncertainty of Digital Soil Maps

The kriging approach as described above can be validated either by comparing the estimates at a location for which the values are known or through cross validation approach to know the accuracy of the product. If there is sufficient amount of data is available, then it was randomly partitioned into training and testing database and the kriging system developed with training database is evaluated in the training database. Otherwise, in the cross validation approach, a data point or a group of data points are eliminated and then kriging system was developed which was further tested on the left out point or points. In the above procedure, the elimination, development and testing steps are repeated several times. Thus the cross validation may be leave-one-out cross validation or *k*-fold cross validation. In the leave-one-out cross validation approach, one data point is eliminated each time and the process is repeated for *n* times, where *n* is the number of data points available in the database. In the *k*-fold cross validation approach, the dataset is divided into *k* subsets out of which one subset is kept aside while developing the kriging system using ($k - 1$) subsets, which then tested on left out subset. Thus, leave-one-out cross validation may be considered as a special case of *k*-fold cross validation when k = 1. While testing the developed kriging system on testing database, error is calculated as the difference between estimated and observed values. Thus the accuracy can be judged based on the following three validation indices, e.g. mean error (ME), root-mean-squared residual (RMSR) or root mean square error and mean square deviation ratio (MSDR):

$$ME = \frac{1}{n}\sum_{n}^{i=1}[Z(x_i) - \hat{Z}(x_i)] \tag{1.12}$$

$$\text{RMSR} = \sqrt{\frac{1}{n}\sum_{n}^{i=1}[Z(x_i) - \hat{Z}(x_i)]^2} \tag{1.13}$$

$$\text{MSDR} = \frac{1}{n}\sum_{n}^{i=1}\frac{[Z(x_i) - \hat{Z}(x_i)]^2}{\hat{\sigma}^2(x_i)} \tag{1.14}$$

where $Z(xi)$ is the observed values of the variable at the location *xi*, $\hat{Z}(x_i)$ is the predicted values with variance σ^2 at the location *xi* and *n* is the number of sampling location. The RMSR estimates the accuracy of prediction (e.g. larger RMSR values indicate less accuracy of prediction). The MSDR measures the goodness of fit of the theoretical estimate of error (Bishop and Lark 2008). If the correct semivariogram model is used, the MSDR values should be close to 1 (Lark 2000).

Apart from accuracy, the uncertainty of digital soil map is also very important which indicates the reliability of the product. Uncertainty of an estimate generally indicates the confidence interval at a certain significance level and is quantified by standard error of mean. In the kriging procedure, estimates are given by a mean prediction along with its variance which is also known as kriging variance. It is to be noted here that in the kriging procedure kriging variance is targeted to be minimum while estimating soil attributes at an unknown location. Therefore, kriging estimates are always associated with kriging variance and most times we are neglecting it. An estimate may be highly accurate but may be less uncertain which means that the estimated value is very close to observed value but the confidence interval of the estimate is very large. For example, sand content estimate for a particular grid point of a digital soil map is 70% with the variance of estimate as 15%. Thus, the 95% confidence interval of this estimate will be $70 \pm 1.96 \times \sqrt{15} \cong 70 \pm 7.6$. It indicates that out of 100 times, 95 times the estimate will be in the range

62.4–77.6 and 5 times it may be outside the above range. Therefore, if the range is quite high or the interval is large, the estimate is highly uncertain. Therefore, one should be careful before presenting the digital soil map products and it is always advisable to produce estimate map along with standard deviation map or variance map.

1.7 Scale Issues of Digital Soil Mapping

Another important aspect of DSM is the scale, which is generally defined by the triplet of spacing, extent and support. The scale of a digital soil product is quite different from the mapping scale. Soil maps prepared through soil survey efforts are generally available at a particular scale, e.g. one million scale (1:1,000,000) or ten thousands scale (1:10,000), etc. It indicates that 1 mm in a printed map represents 1 km in the real field for a one million scale map. However, such representation of scale for a digital soil product is irrelevant because it is occasionally or never printed as hard copy. Apart from it, the digital products are defined with a certain spatial resolution. If the spatial resolution is fine, pixel numbers will be large which means it can be zoomed to a very high level otherwise if it is coarse resolution; pixel numbers in the image will be less and cannot be zoomed to a high level. The resolution of the spatial product generally indicates the spacing in scale triplets. Triplets of scale in a digital soil map can be easily understood from Fig. 1.1, which is nicely described in Blöschl and Sivapalan (1995). The spacing defines the separation distance between two grid points of a map in X-axis and Y-axis, e.g. resolution of a digital soil map is 5 × 5 m. The extent defines the difference between minimum and maximum length of the map in pixel numbers along both X-axis and Y-axis direction, e.g. the size of a digital image is 1000 × 1500 indicating 1000 pixels in X-axis direction and 1500 pixels in Y-axis direction. The support defines the surface area for which the estimates or values are given, e.g. in most digital soil product support is point which is generally the centre point of a pixel. However, in case of block kriging products, the support is block size.

Therefore, whenever we prepare digital soil map from legacy soil data, we need to define the scale triplets at which it will be prepared. As depicted in Fig. 1.2, the possible extent of digital soil maps may vary from plot scale to national scale. Therefore, before proceeding ahead for creating digital soil maps, we need to confirm whether sufficient data is available to prepare a map for a particular scale. From high spatially distributed legacy soil data available for a large extent, e.g. State level soil database, it is not desirable to develop maps to be used in a very lower level in the hierarchy for assisting land management decision. For this purpose, much more sampling density is required which needs additional sampling effort.

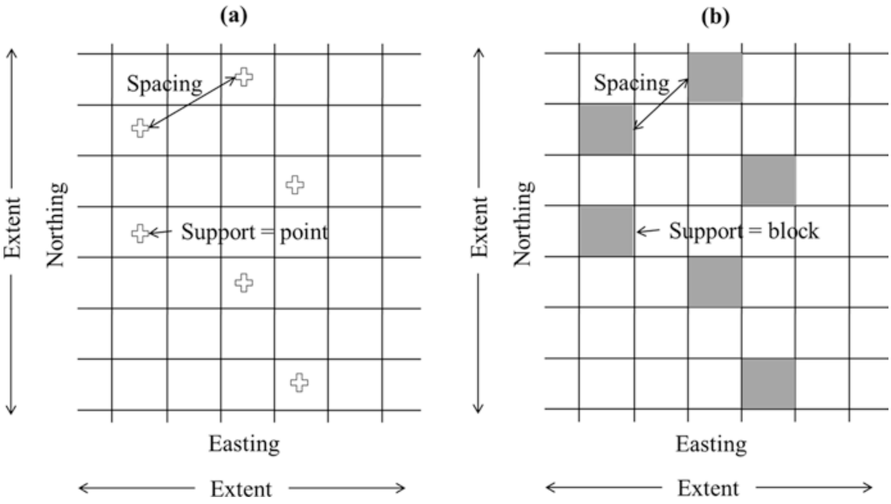

Fig. 1.1 Definition of the scale triplet (spacing, extent and support); (**a**) sampling design with point support (**b**) similar sampling design but with block support

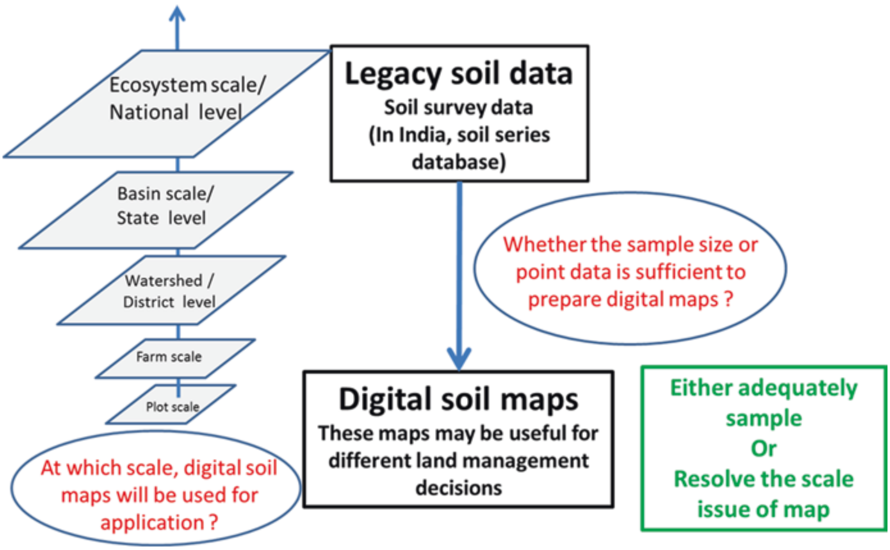

Fig. 1.2 Scale issues in digital soil mapping

1.8 Pedotransfer Functions and Digital Soil Mapping

1.8.1 Pedotransfer Functions

Pedotransfer functions (PTFs) are mathematical models by which complex soil properties, e.g. soil hydraulic properties can be estimated from basic soil properties, which are easy to measure (Bouma 1989). Multiple regression equations are most commonly followed to develop PTFs, however, several advance techniques, e.g. regression tree, artificial neural network, nearest neighbourhood, etc., have been used. Here we discuss different type of PTFs and commonly used predictor variables to develop PTFs for hydraulic properties.

1.8.1.1 Class PTFs and Continuous PTFs

Within PTFs subdivision is made between class PTFs and continuous PTFs (Wösten et al. 1999). Class PTFs are based on the assumption that similar soils exhibit similar hydraulic properties and the PTFs are developed for a particular soil groups such as soil texture (Carsel and Parrish 1988; Wösten et al. 1995; Leij et al. 1996). A continuous PTF provides continuously varying estimates of hydraulic properties using actually measured percentages of particle size distributions, OC content and ρb across different soil groups (Rawls and Brakensiek 1985; Veerecken et al. 1989; Rawls et al. 1991; Williams et al. 1992). For developing class PTFs, different grouping of soils are defined. Soil texture is the most widely used grouping criteria for developing class PTFs (Rawls et al. 1982; Cosby et al. 1984; Wösten et al. 1999). Franzmeier (1991) showed that grouping soils by genetic horizons and parent materials is preferable to grouping by texture in determining gravimetric water content at −33 and −1500 kPa. Pachepsky et al. (1996) also grouped soils using genetic classification. Santra (2001) tried to group soil based on soil taxonomy and horizons and developed class PTFs for different horizons of Typic Ustochrept and Typic Ustifluvent. Wösten et al. (1990) grouped soil based on an assessment of the functional behaviour of different horizons. A grouping by mineralogy and genesis of soil before developing PTF was suggested by Puckett et al. (1985). Bachmann and Hartze (1992) suggested using similarity in particle size distributions instead of using textural classes to group soils.

1.8.1.2 Point PTFs, Parametric PTFs and Semi-Physical Approach

Teitje and Tapkenhenrichs (1993) classified PTFs based on point, parametric and semi-physical estimation methods. Point estimation methods follow a direct approach by estimating water contents at predetermined pressure heads (e.g. Gupta and Larson 1979; Rawls et al. 1982; Minasny et al. 1999; Tomasella et al. 2003; Børgesen and Schaap 2005) and estimating hydraulic conductivity at saturation (Cosby et al. 1984; Saxton et al. 1986; Minasny et al. 1999; Santra et al. 2008). Although the point estimation methods are simple in approach but have the disadvantage of large number of regression equations required for full characterization of water retention curve.

Parametric methods estimate the parameters of water retention or conductivity functions (Rawls and Brakensiek 1985; Wösten and van Genuchten 1988; Veerecken et al. 1989; Scheinost et al. 1997; Minasny et al. 1999; Minasny and McBratney 2002; Santra et al. 2008). In this approach, the parameters of water retention or conductivity function are first optimized from measured water retention or hydraulic conductivity data. Among available water retention functions, the model proposed by van Genuchten (1980) was mostly used by several researchers to develop parametric PTFs.

Semi-physical methods use the shape-similarity concepts between cumulative particle size distributions with soil water retention characteristics (Arya and Paris 1981; Haverkamp and Parlange 1986). These models first translate particle size distribution into an equivalent pore-size distribution model, which in turn is related to distribution of water contents and associated pressure heads. In this approach, the measured water retention curve is described with an analytical function. Based on this, a pore-size distribution is derived, which, in turn, is used to predict a hydraulic conductivity function assuming water flow through cylindrical soil pores.

1.8.1.3 Predictor Variables in PTFs

Typically PTFs are developed with basic soil properties as input variables, e.g. sand, silt, clay, organic carbon contents, etc. (Rawls et al. 1982; Veerecken et al. 1989; Tomasella and Hodnett 1998; Wösten et al. 1999; Schaap et al. 2001). Topographic features as derived from digital elevation model, e.g. slope, curvature, topographical wetness index, etc., (Pachepsky et al. 2001; Romano and Palladino 2002) and vegetation indices, e.g. normalized difference vegetation index (Sharma et al. 2006) are also considered as predictor variables in PTFs. Soil spectral signatures and derived indices from measured spectral data have recently been used as predictor variable in PTFs and such type of functions are specially termed as spectrotransfer functions (Lagacherie et al. 2008; Santra et al. 2009, 2015).

1.8.2 Application of PTF: Soil Moisture Calculator

During last two decades several PTFs models have been developed at different parts of the world because these PTF models are not portable across climatic regions. Now, there is a requirement to apply these PTFs in managing soil resources. For this purpose, we developed PTF models for hot arid ecosystem of India and further transferred these models into user interface for their wide applicability.

Soil moisture content at field capacity (1/3 bar) and permanent wilting point (15 bar) are two critical constants for determining the availability of soil water for plant growth and thus guide the farmers to take decision on timing and quantity of irrigation. These two soil moisture constants are largely governed by sand and clay content of soil and also on organic carbon content. Keeping in view these inherent relationships, regression based pedotransfer functions (PTFs) have been developed to estimate soil water retention at 1/3 bar (FC) and 15 bar (PWP) from available soil data in hot arid western India. The developed models showed satisfactory

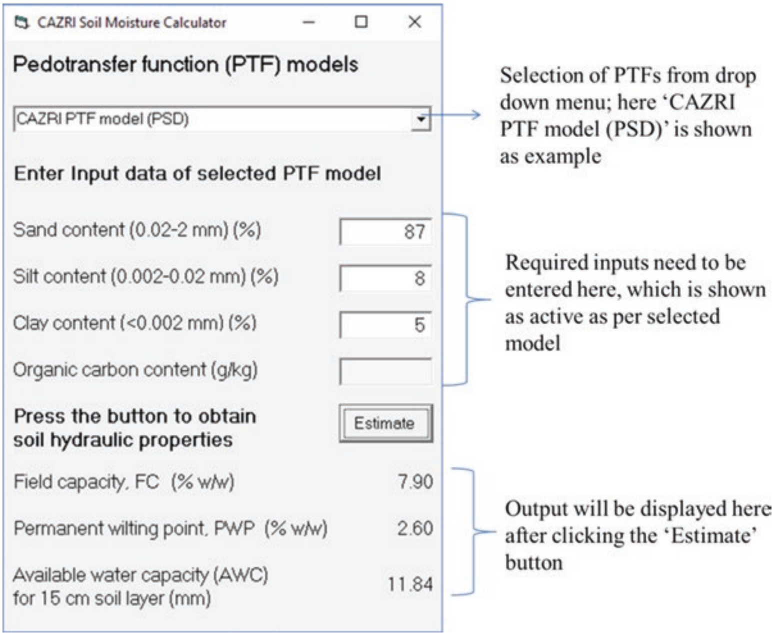

Fig. 1.3 CAZRI soil moisture calculator

performance while validated and tested in independent datasets and even found better than several established PTFs available in literature. For wide applicability of the developed PTFs, a user-friendly soil moisture calculator, 'CAZRI soil moisture calculator', was developed; it may be downloaded from http://www.cazri.res.in/soil-moisture-calc.php (Fig. 1.3). First, using a pull-down menu, users must choose the appropriate PTF. Subsequently, for any field, users must enter the sand, silt, clay and OC content. Upon pressing 'enter', the FC and PWP are calculated for the upper 15 cm.

For arid regions in India, we recommend the PTF_{SAWI} models that consider either the PSD or PSD + OC category depending on the availability of input data. In the CAZRI soil moisture calculator these models are referred to as CAZRI PTF model. However, for dry lands elsewhere in the world, global PTFs may be selected using the drop-down menu for model selection. Apart from dry lands, the calculator may also be used elsewhere in India or tropical countries of the world, since it also contains the robust PTF model of Tomasella and Hodnett (1998), Adhikary et al. (2008) and Chakraborty et al. (2011).

Knowledge on estimated critical soil moisture constants may guide the farmers to apply the right amount of irrigation water at the right time, possibly with support of an extension service. For example, in a farmer's field with sand, silt and clay content of 87, 8 and 5%, respectively, the estimate of soil water content at FC and PWP will be 7.90 and 2.60% (g/g), respectively, if CAZRI PTF model (PTF_{SAWI}) with PSD category of input data is selected. These estimates will further lead to an estimate of maximum plant available soil water of 11.8 mm in surface soil (0–15 cm) assuming an average bulk density of 1.49 Mg m^{-3} for arid western India, as found in the SAWI database. For example, if a farmer wishes to apply irrigation at 50% soil moisture depletion, then he should irrigate the field when soil water content dries to 5.25% (g/g) from FC level [soil moisture content after 50% depletion = FC − 0.5 × (FC-PWP)] and the required quantity of irrigation water will be 59.2 m^3 ha^{-1} for bringing the soil moisture level of the 0–15 cm soil layer again to FC level [required amount of water = (FC − soil moisture) × bulk density × soil depth × area to be irrigated]. In the above calculation, a linear decrease in soil water content during the process of soil drying was assumed. For a more accurate estimation of the required amount of water, a curvilinear relationship between water potential (h) and soil water content (θ) may be considered, but this would require tedious field monitoring of soil water suction levels using a tensiometer. The CAZRI soil moisture calculator developed in the context of this study may help extension workers to assist farmers in saving the scarce water resources, while maintaining the required productivity.

1.8.3 Integration of PTF and DSM

Pedotransfer function can also be applied to prepare map of soil hydraulic properties, which are time consuming and tedious to measure. This can be achieved in two ways: (1) mapping the basic soil properties from point data by using geostatistical approach and then joining raster map of basic soil properties using PTF equation to obtain hydraulic property map, (2) estimating soil hydraulic properties at point location for which measured basic soil properties are known and then mapping the estimated hydraulic properties through geostatistical approach (Bechini et al. 2003; Santra et al. 2008). However, in both cases, error propagation needs to be quantified for further applicability of developed maps. Here, we have shown one application where soil water retention maps were prepared from maps of basic soil property.

1.8.3.1 Spatially Distributed Soil Samples in a Farm Scale

A study was carried out at the experimental farm of ICAR-Indian Agricultural Research Institute, New Delhi, India lying between 28°37′–28°39′ N and 77°8′30″–77°10′30″ E and at an elevation of 217–241 m above mean sea level to characterize spatial variation of soil properties within the farm (Santra et al. 2008). The climate of the study area is semi-arid in nature and June is the hottest month whereas January is the coldest month. Average daily maximum temperature for a month during summer (May, June and July) varies between 43.9 and 45 °C whereas average daily minimum temperature drops to a lowest of 5 °C in the month of January. Annual rainfall of the area is 708.6 mm out of which 597 mm (84%) is received during June–September and the rest during winter months (November–March). For carrying out the spatial analysis of soil properties, samples were collected from 50 locations of the farm (243 ha) covering 6 soil series under 2 soil subgroups (Fig. 1.4).

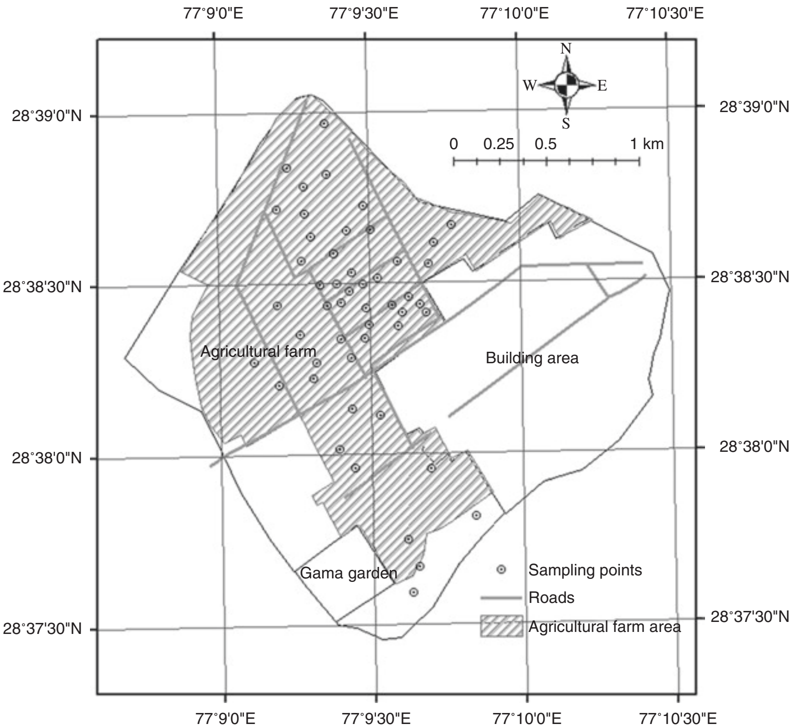

Fig. 1.4 Location of sampling points in experimental farm of Indian Agricultural Research Institute (IARI), New Delhi (Source: Santra et al. 2008)

1.8.3.2 Digital Soil Mapping of Basic Soil Properties

Semivariograms of bulk density, soil organic carbon (SOC) content, silt content and clay content of experimental farm of IARI were computed from developed spatial data. Different theoretical models were tested to fit the calculated semivariogram and Gaussian model was found as the best fit in most cases. In case of bulk density, silt content and clay content, range of spatial variation varies from 900 to 1200 m, which indicates that these soil properties separated with lag distances below 1 km are spatially correlated with each other. Beyond this range value, the variation is considered as random variation. Soil organic carbon content was found spatially correlated for a shorter lag distance than bulk density and primary soil separates, which is about 500 m.

Digital maps of bulk density, silt content, clay content and SOC content were prepared using calculated semivariogram parameters using ordinary kriging approach. Spatial map of these basic soil properties for 0–15 cm soil layer was presented in Fig. 1.5. Southern part of the farm was found with higher bulk density (>1.59 Mg m^{-3}) than other parts of the farm (Fig. 1.5a). For North-Western part of the farm, bulk density was found 1.47–1.52 Mg m^{-3}. Spatial map of organic carbon content (0–15 cm) (Fig. 1.5b) showed that 80% of the farm area had medium organic

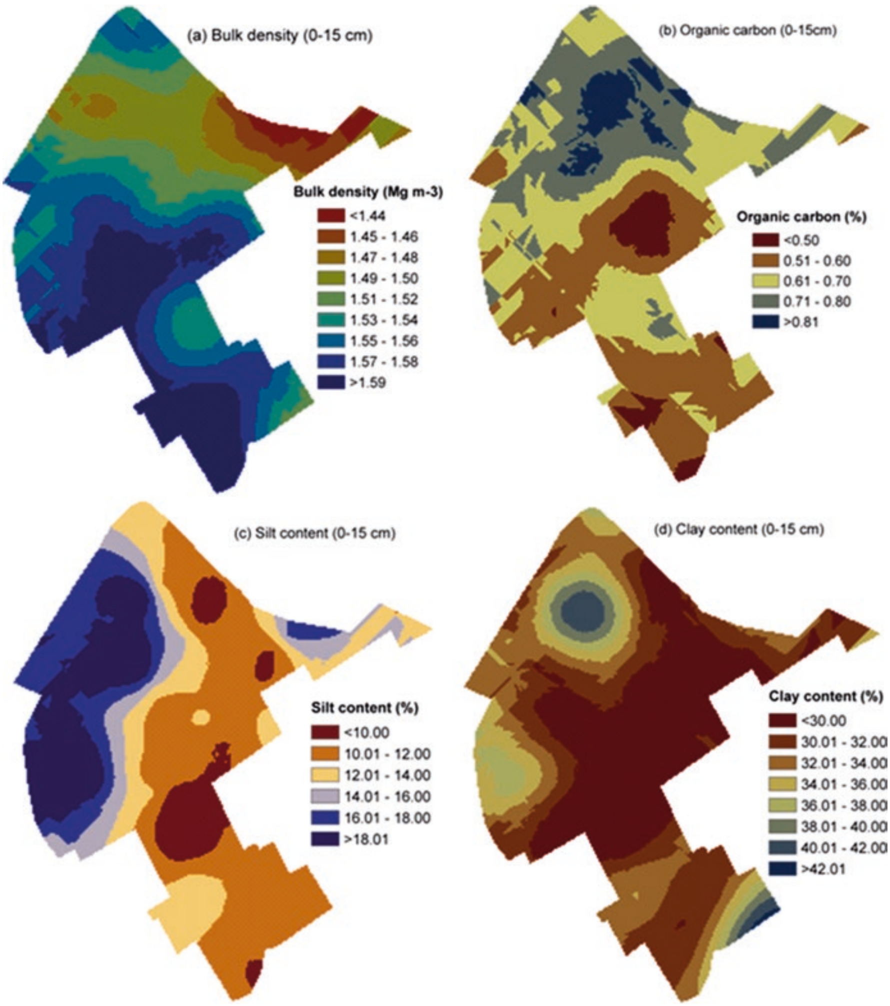

Fig. 1.5 Kriged maps of soil properties for 0–15 cm soil depth; (**a**) bulk density (Mg m^{-3}), (**b**) organic carbon content (%), (**c**) silt content (%) and (**d**) clay content (%) (Source: Santra et al. 2008)

carbon content (0.5–0.75%). Spatial map of silt content (%) showed a decrease in its content from East to West direction (Fig. 1.5c). Western part of the farm was found slightly higher in silt content than rest portion. Figure 1.5d shows that except some few patches, clay content was <34% in most part of the study area.

1.8.3.3 Pedotransfer Functions for Estimating θ_{FC} and θ_{PWP}

For combining the surface map of basic soil properties showed above, PTF models are required. For this purpose, several PTFs were developed and tested with existing

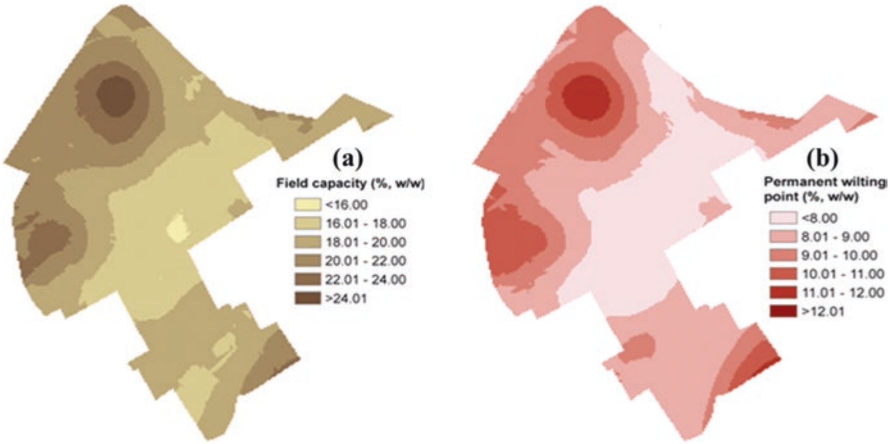

Fig. 1.6 Spatially predicted map of water content for IARI farm; (**a**) water content at field capacity for 0–15 cm soil depth, (**b**) Water content at permanent wilting point for 0–15 cm soil depth (Source: Santra et al. 2008)

PTFs available elsewhere. The PTFs developed from the available soil data in benchmark soils of India were found appropriate and best, which are given below:

$$\theta_{FC}(\%,\mathrm{w/w}) = 21.931 \quad 0.20564 \times \mathrm{sand} + 0.175 \times \mathrm{clay} + 4.6737 \times OC\,(R^2 = 0.89) \tag{1.15}$$

$$\theta_{PWP}(\%,\mathrm{w/w}) = 8.7255 \quad 0.092946 \times \mathrm{sand} + 0.15944 \times \mathrm{clay}(R^2 = 0.78) \tag{1.16}$$

where sand is the per cent sand content (0.05–2 mm), clay is the per cent clay content (<0.002 mm) and OC is the per cent organic carbon content in the soils.

1.8.3.4 Integration of PTFs and Digital Soil Maps to Obtain Map of Complex Soil Properties

Spatial maps on water content at field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) prepared through linking soil maps on basic properties (see Fig. 1.5) and PTFs (see Eqs. 1.15 and 1.16) are presented in Fig. 1.6. Water content at field capacity increases in East to West direction of the farm for both surface and subsurface layer. The value of θ_{FC} (%, w/w) varies from 15.88 to 25.48%. Maximum water content is found at North-Western part of the farm where clay content was highest among all parts of the farm. Similar type of spatial trend is also observed for the map of θ_{PWP}. The value of θ_{PWP} (%, w/w) varies from 6.72 to 11.92%. Spatial prediction uncertainty of the developed map of θ_{FC} and θ_{PWP} was calculated through comparing them with their observed values at 50 locations of the study area, which was found satisfactory. The approach followed to prepare hydraulic property map involves propagation of interpolation error multiple times, but one advantage of this approach is the potential use of spatial maps of basic property for farm level planning or modeling environmental processes.

These maps may serve the guideline for proper irrigation scheduling because water content at FC and PWP are considered as two important moisture constants for plant growth. Besides these, spatial maps of bulk density and particle size distribution may lead to selection of crops which needs specific soil physical environment. For example, North-Western part of the farm shows high clay content and bulk density which lead to low permeability of soil and is suitable for maintaining proper biophysical environment for growth of rice crop. The soils of central part of the farm are sandy loam in texture and best suitable for rabi crops like mustard, wheat, grams, etc. Therefore, identifying crop specific zones in the farm may be planned based on these spatial maps of soil properties. Although such type of blocking of large farm area is presented in few cases based on field expertise but such maps may lead to segregating the farm in precise zones, which is the need for precision agriculture. In this study we have showed only the maps of soil physical properties which will help in better water management. Such type of study in farm scale may be extended for major nutrients (N, P, K) required for plant growth and thus may help in site-specific nutrient management.

1.9 Hyperspectral Signature of Soil and Its Use in DSM

1.9.1 Soil Reflectance in VIS-NIR-SWIR

Reflectance spectroscopy in the VNIR-SWIR region (350–2500 nm) of the electromagnetic spectrum has been used for accurate and fast determination of soil properties (e.g. clay content, organic matter content, soil nitrogen content, Fe-containing minerals, salt content, soil hydraulic conductivity, soil water retention, soil aggregate size distribution, crop residue content on soil surface, weathering indices, etc.) from prepared soil samples (Henderson et al. 1989; Morra et al. 1991; Ben-Dor and Banin 1995; Ben-Dor et al. 1997; Chang et al. 2001; Dunn et al. 2002; McCarty et al. 2002; Reeves et al. 2002; Shepherd and Walsh 2002; Islam et al. 2003; Huang et al. 2005; Stevens et al. 2006; Viscara Rosel et al. 2006; Wang et al. 2006; Lagacherie et al. 2008; Brown et al. 2006; Santra et al. 2009; Sarathjith et al. 2014; Sahadevan et al. 2014; Chakraborty et al. 2014; Mohanty et al. 2016; Sarathjith et al. 2016). Proximal spectral reflectance of soils at VIS-NIR-SWIR region of the spectrum generally shows three characteristics features: overall brightness of the reflectance spectra, slope of the reflectance spectra from visible to near infrared and three prominent absorption features at 1414, 1913 and 2207 nm (Fig. 1.7).

Leone and Somer (2000) discriminated between soil development and soil degradation using laboratory reflectance spectra in the VNIR region. Dematte et al. (2004) showed that laboratory reflectance spectra in the VNIR region can be used to develop a methodology to describe the variation of parent material along a toposequence. They also showed that reflectance spectra may be used to group soils according to different tillage systems.

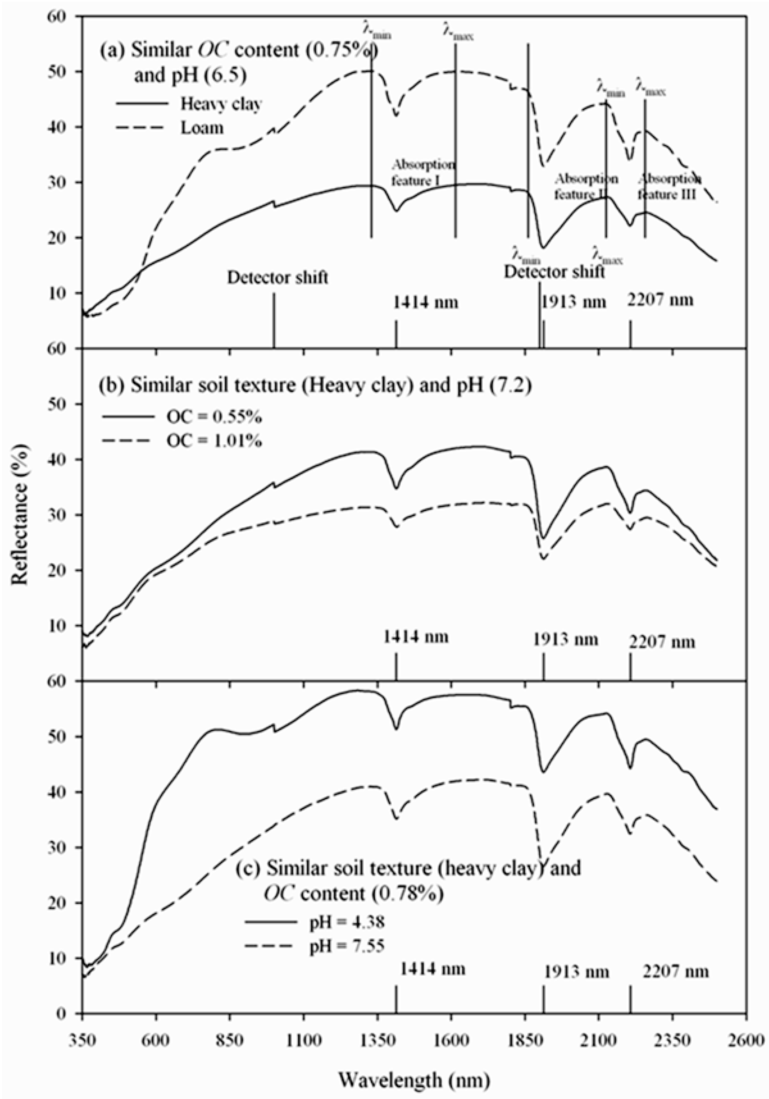

Fig. 1.7 Reflectance spectra of soil samples (**a**) for two soil textural classes with similar OC content and pH and (**b**) for different organic carbon content with similar soil texture and pH and (**c**) for different pH with similar soil texture and OC content (Source: Santra et al. 2009)

Estimation of soil properties using reflectance spectra obtained through hand-held spectroradiometer may be accurate and irreplaceable for field studies, but cannot provide a suitable solution for large areas. Modern satellite and aircraft based remote sensors may be advantageously used for such purpose. Hence, several research workers have used simulated band reflectance corresponding to spectral channels of various remote sensing sensors to correlate with soil properties (Leone and Escadafal 2001; Wang et al. 2006; Lagacherie et al. 2008). Some have tried to correlate the band reflectance with soil color, which is commonly used by soil survey people for assessing soil properties (Escadafal et al. 1989; Mathieu et al. 1998). However, all such efforts have been generally based on reflectance spectra collected under controlled laboratory condition and hence ignored several other attenuation factors in real situations (e.g. presence of gravels, soil moisture, soil roughness in field and atmospheric turbidity). Therefore, the radiometric performance typically measured by signal-to-noise ratio (SNR) is lower for remote sensing sensors (100–500:1) than spectroradiometer (>1000:1). Recently, Lagacherie et al. (2008) have tried to quantify all these attenuation factors in estimating clay content and $CaCO_3$ content. From the above discussion, it is clear that an array of soil properties may be estimated from reflectance spectroscopy or even with the use of simulated/observed band reflectance of remote sensing sensors with reasonable accuracy.

1.9.2 Soil Spectrotransfer Function Modeling for DSM

Considering the relationship between basic soil properties and soil spectral reflectance, it is possible to estimate basic soil properties from proximally measured soil spectral signatures. Therefore, it is hypothesized that complex soil properties, e.g. soil hydraulic properties may be estimated from spectral data since complex soil properties and basic soil properties are related with each other. Thus suitable spectrotransfer functions (STFs) may be developed to estimate soil hydraulic properties from spectral data similar to PTFs approach. Till now, only few studies indicated that soil hydraulic properties may be related to proximal spectral reflectance (Thine et al. 2004; Janik et al. 2007; Santra et al. 2009). Apart from soil hydraulic properties, several other soil properties may be estimated from spectral data and reports are also available on this aspect (Sahadevan et al. 2014; Mohanty et al. 2016). For example, Thine et al. (2004) characterized soil degradation status using relationships between soil hydraulic properties and spectral reflectance over the VNIR region. Janik et al. (2007) showed the estimation approach of soil water content at various matric pressure heads using calibrated reflectance spectra in mid-infrared (MIR) region.

Santra et al. (2009) developed STFs for estimation of van Genuchten soil water retention parameters (α and n) and saturated hydraulic conductivity (Ks) from soil reflectance spectra measured from disturbed soil samples collected from a hilly watershed in Eastern India. Soil spectral indices, e.g. principal components, continuum removal (CR) factor and derived band reflectance were found well correlated with basic soil properties. Soil spectral reflectance at most region of reflectance spectra was found significantly correlated ($|r| = 0.3–0.6$) with sand content, silt content, clay content, pH, EC and van Genuchten parameters. Such correlation helped to develop spectrotransfer functions for soil hydraulic properties. Both point STFs [for $\ln(Ks)$] and parametric STFs [for van Genuchten parameter $\ln(\alpha)$ and n] were developed using multiple linear regression approaches and are presented in Table 1.1.

Table 1.1 Spectrotransfer functions for estimating saturated hydraulic conductivity and van Genuchten parameters from basic soil properties, and spectral reflectance of soil in visible and near-infrared region (Source: Santra et al. 2009)

Hydraulic parameter	Predictor variables in PTF	Pedo- and spectrotransfer functions
ln(*ks*)	Band reflectance	4.7038 − 0.3397 × Band-1[a] + 0.0754 × Band-6[a]
	CR factors	3.925 + 10.7504 × CR_{1414}[b] + 3.3991 × CR_{1913}[b] − 15.0937 × CR_{2207}[b]
	ASD full spectrum	3.0416 − 0.006 × PC1[c] + 0.0673 × PC2[c] − 0.0453 × PC3[c]
ln(α)	Band reflectance	0.4533 − 0.1439 × Band-2
	CR factors	−0.0969 + 35.5831 × CR_{1414} − 20.2724 × CR_{1913} − 22.0356 × CR_{2207}
	ASD full spectrum	−2.2427 − 0.0158 × PC1 + 0.0238 × PC2 + 0.004 × PC3
n	Band reflectance	1.2238 + 0.0232 × PC1 + 0.0166 × PC2
	CR factors	0.614 + 0.8818 × CR_{1913}
	ASD full spectrum	1.225 + 0.0013 × PC1 − 0.0002 × PC2 − 0.0041 × PC3

[a]Band-1, Band-2, Band-4 and Band-6 are the band reflectance in 450–520 nm, 520–600 nm, 760–900 nm and 2080–2350 nm, respectively
[b]$CR_{1414\ nm}$, CR_{1913} and CR_{2207} are continuum removal factors at 1414 nm, 1913 nm and 2207 nm, respectively
[c]PC1, PC2 and PC3 are first, second and third principal components, respectively, obtained after principal component analysis of respective high dimensional predictor variables

Results showed that although the performance of STFs was not superior than the corresponding PTFs for estimating hydraulic properties, but it may be used in case of unavailability of PTFs. In few cases, the STFs perform comparable to PTFs. Specifically, STFs developed with CR factor at 1414 nm (CR_{1414}), CR factor at 1913 nm (CR_{1913}) and CR factor at 2207 nm (CR_{2207}) performed similar to PTFs developed with basic soil properties. The STF developed with CR factors for estimating α performed better than the corresponding PTF.

1.10 Case Study of Digital Soil Mapping

1.10.1 Soil Carbon Mapping

Soil organic carbon (SOC) content plays a critical role in maintaining soil productivity for supporting crop production. Recently, in the context of climate change, lot of focus has been put on to reduce the atmospheric CO_2 level through a chain of increasing vegetation carbon pools first and then to store them as soil carbon pool (Watson et al. 2000; Kerr 2007; Lal 2008). For quick assessment of soil carbon management programmes, it is important to know about the amount of soil carbon stored in an agricultural farm through adoption of a specific land management practices. In the following sections, a study on SOC mapping through geostatistical approaches is presented to show the effect of different farm management practices on SOC contents. The study was carried out at an agricultural farm from hot arid ecosystem of India located at Badoda village of Jaisalmer district, Rajasthan. The farm lies between 26°52′30″–26°53′30″ N and 71°12′15″–71°13′15″ E and total area of the farm was 76.12 ha, 85.38% of which was under cultivation in four main blocks: block A, B, C and D (Fig. 1.8).

Cultivation in these four blocks had been started with the help of tube well irrigation. The first tube well within the farm was dug in block A in the year 1999. Afterwards tube wells were dug I the block D, B and C and cultivation was successively started in the year 2003, 2005 and 2008, respectively. Average depth of groundwater below ground level in these four tube wells in the year 2009 was about

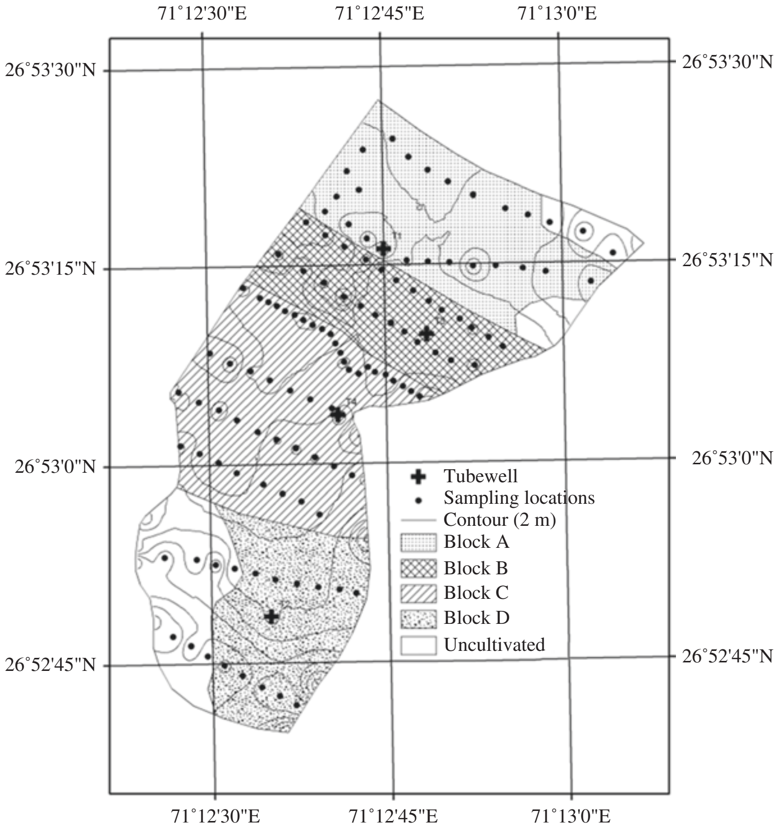

Fig. 1.8 Layout of the agricultural farm along with the location of sampling points within it from hot arid ecosystem of India located at Badoda village of Jaisalmer, Rajasthan (Source: Santra et al. 2012)

95 m. Groundnut, mustard, mung bean, cluster bean and wheat were the major crops grown in the farm. The cultivation in a particular plot had been practiced once in a year and kept the land fallow for remaining periods since the year 1999. Groundout was the major crop for block A and C. Mustard and mung bean were mostly cultivated at the eastern part of the block A, B and C. Wheat was the major crop in the block D. Cluster bean was cultivated in scattered small areas of the farm.

Soils of the farm were sandy to loamy sand with abundant presence of freely available $CaCO_3$ (5–10%) and taxonomically defined as Typic Torripsaments (Singh et al. 2007). A total of 116 surface soil samples (0–15 cm) were collected from different locations of the farm (see Fig. 1.8) and SOC contents were determined in the laboratory using wet digestion method (Walkley and Black 1934). Average SOC content of the farm was found 1.66 g kg^{-1} and ranged from as low as 0.11–6.34 g kg^{-1}.

1.10.1.1 Spatial Variation of SOC Content and Its Mapping

Spatial variation of SOC content was determined using semivariogram plot which is defined as the plot of semivariogram (γ) versus lag (h). Omni-directional semivariogram was computed because the presence of directional trend was almost negligible. Computed semivariogram values [γ (h)] for corresponding lag (h) were fitted in standard theoretical semivariogram models using weighed least square technique. Spherical model was found best with the lowest AIC value. Fitted semivariogram structure of SOC content of the farm is depicted in Fig. 1.9.

The nugget (C_0) and sill ($C_0 + C$) were found 0.77 and 2.12, respectively. It was also observed that C_0, which indicates small-scale variation of a regionalized variable, was about 36% of the total sill. Contribution of nugget to total sill may further be reduced by adopting intensive sampling efforts. The range (a) parameter of SOC content was found 146 m. These spatial variation parameters (C_0, C and a) indicated that SOC content was highly variable in two-dimensional space. Specifically the range parameter indicated that spatial variation of SOC might be captured well only through sampling with minimum separation distance ≤150 m. Surface map of SOC content of the farm was further prepared through ordinary kriging (OK) using semivariogram parameters (C_0, C and a). The prepared map of SOC content prepared through OK with a grid size of 5 × 5 m is presented in Fig. 1.10. Accuracy of the prepared SOC map was further evaluated using leave-out-one cross validation approach.

The map of SOC content showed that soils in farm blocks where groundnut is cultivated were comparatively higher in SOC content (1.88 g kg^{-1}) than rest blocks of the farm. Among groundnut cultivated blocks, the highest SOC content (2.51 g kg^{-1}) was observed in the block C and the lowest (0.86 g kg^{-1}) in the block A. Natural fallow lands at south eastern and southern portion of the farm, where deposition of aeolian sands was a common natural process and rocky outcrops with presence of a few grass species of *Eleusine compressa*, *Lasiurus sindicus*, etc., are the dominant landscape features, had the average SOC content of 2 g kg^{-1}. Farm blocks under

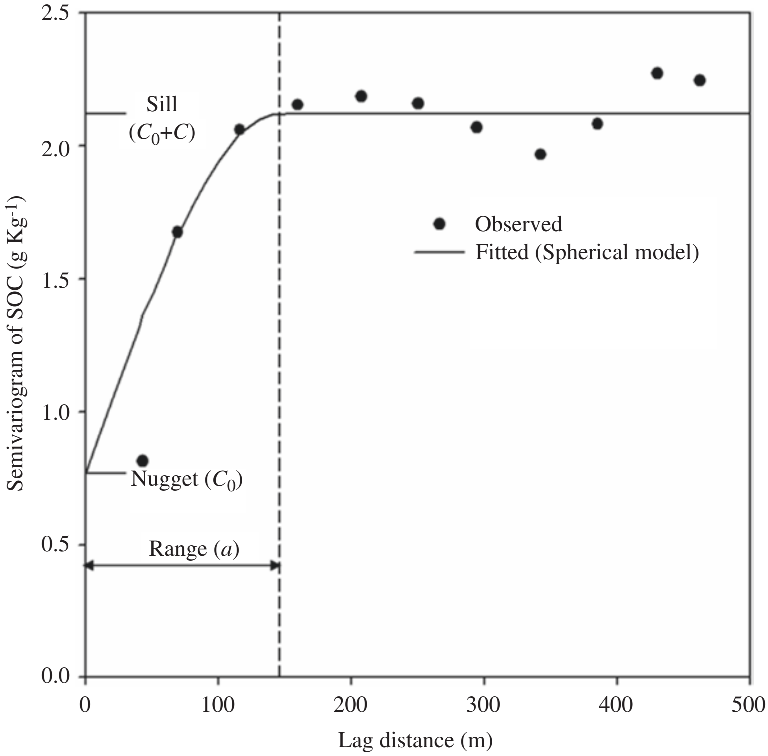

Fig. 1.9 Semivariogram of soil organic carbon content (g kg^{-1}) within the farm area (Source: Santra et al. 2012)

cluster bean, mustard and mung bean cultivation were comparatively lower in SOC content (1.58 g kg^{-1}, 1.54 g kg^{-1} and 0.77 g kg^{-1}, respectively) than rest. Comparatively higher SOC content in groundnut cultivated areas was mainly due to spreading nature of groundnut crop, which protected carbon stock of soil from its loss through wind eroded aeolian sediments by crop coverage on soil surface. Overall, soils under block A of the farm, where cultivation had been done since last 10 years, had the lowest SOC content (1.06 g kg^{-1}). Reversely, the highest SOC content (2.13 g kg^{-1}) was observed in block C, at where cultivation had been done since last 1 year. These showed that cultivation of land even for once in a year had resulted in significant reduction of SOC content specifically in arid areas where wind eroded loss is notable. Disturbances of top soil through cultivation resulted into loose top soils, which further aggravated the rate of SOC depletion through wind erosion events.

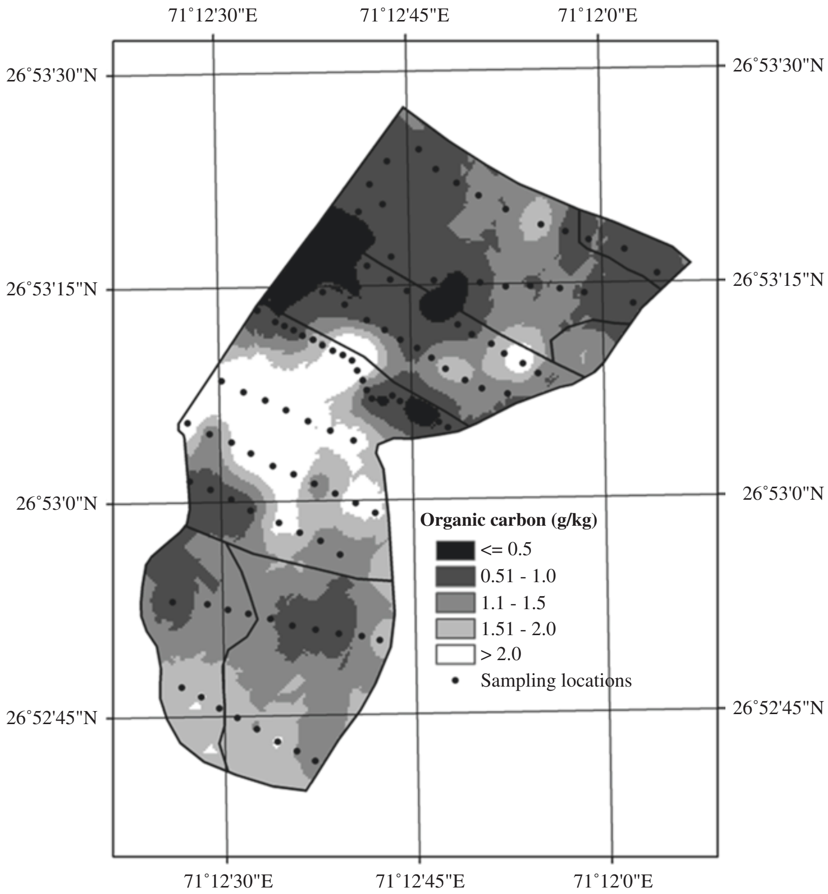

Fig. 1.10 Spatial distribution of soil organic carbon content (g kg^{-1}) of 0–15 cm soil layer in the agricultural farm at Jaisalmer, Rajasthan (Source: Santra et al. 2012)

1.10.1.2 SOC Stock of the Farm

Surface map of SOC content as shown in Fig. 1.10 was further converted to SOC stock density map using the following formula:

$$SOC \text{ stock density} (Mg\, ha^{-1}) = SOC(\%) \times \text{bulk density} (Mg\, \text{m}^{-3}) \times \text{soil depth} (\text{m}) \times 100$$

Total SOC stock of the farm was computed as 272 t with an average SOC stock density of 3.57 t ha^{-1}. Block-wise distribution of SOC stock of the farm is also presented in Table 1.2. Block C covering 28.14% area of the farm contributed 41.41% of the total SOC stock of the farm. In contrary, SOC stock of block A was found 52.38 t, which was about 19.26% of the total SOC stock of the farm but it may be noted that the block covers 23.84% of the farm area. Here it is also to be noted that cultivation had been done in block A since last 10 years from the year 1999 whereas

Table 1.2 Soil organic carbon stock in 0–15 cm soil layer of four blocks of the farm under cultivation for different time periods (Source: Santra et al. 2012)

Blocks of the farm	Years of cultivation	Area (ha)	SOC stock (t)	SOC stock density for 0–15 cm soil layer (t ha^{-1})
Block A	10	18.15 (23.84)	52.38 (19.26)	2.89
Block B	4	11.86 (15.58)	36.36 (13.34)	3.06
Block C	~1	21.42 (28.14)	112.68 (41.41)	5.26
Block D	6	13.56 (17.81)	54.97 (20.20)	4.05
Others	–	11.13 (14.62)	15.70 (5.77)	1.41

in the block C cultivation had been started in the year 2008. These results showed that intensive crop cultivation on loose sandy soils in hot arid areas may deplete the SOC stock at a fast rate. Among cultivated areas of the farm, SOC stock density was found higher in those plots where cultivation had been practiced for a short period (5.26 t ha^{-1}) than those plots where cultivation had been practiced since long (2.89 t ha^{-1}). It was also to be noted that in areas with rocky outcrops of the farm had SOC stock density of 1.41 t ha^{-1}.

1.10.2 Soil Mapping Using Hyperspectral Signatures

1.10.2.1 Linear Model for Estimating Soil Properties from Spectral Signatures

In a study on hyperspectral characterization of arid soils in western Rajasthan, good correlation was observed between spectral signatures and soil properties. Based on these significant correlations, linear regression models were developed to estimate soil properties from principal components (PCs) of spectral signatures and derived band reflectance corresponding to IRS P6 and Landsat OLI bands. The linear models using band reflectance are presented in Table 1.3. Before developing these models, stepwise regression was carried out in both forward and backward approach to select significant band reflectances to develop the model.

Stepwise analysis revealed that *B*2 and *B*3 band of IRS P6 were selected in most cases whereas band reflectance in SWIR region (*B*5) has been additionally selected as significant input for sand and clay content. In case of pH and EC, linear models involving band reflectance corresponding to IRS P 6 bands were not found satisfactory to estimate these soil properties from band reflectance data. Estimation of sand, silt and clay was found better with the help of principal components than the band reflectance corresponding to IRS-P6 bands. However, it is to be noted here that OC can be predicted better using band reflectance ($R^2 = 0.27$) than using PCs ($R^2 = 0.12$).

Table 1.3 Developed spectral algorithms for estimating soil properties using derived IRS-P6 band reflectance and Landsat-8 OLI band reflectance from measured soil reflectance spectra in VIS-NIR-SWIR region (Source: Santra et al. 2015)

Model type	Model equation	R^2
Derived IRS-P6 band reflectance based model[a]	pH = 7.70 + 4.66 × *B*2 − 10.76 × *B*3 + 11.81 × *B*4 − 4.07 × *B*5	0.02
	EC = 278 − 1319 × *B*4 + 882 × *B*5	0.02
	OC = 1.11 + 3.82 × *B*2 − 5.64 × *B*3	0.27
	Sand = 66.3 − 304.5 × *B*2 + 605.7 × *B*3 − 366.3 × *B*4 + 88.1 × *B*5	0.20
	Silt = 11.53 + 157.52 × *B*2 − 264.82 × *B*3 + 102.10 × *B*4	0.17
	Clay = 18.19 + 109.65 × *B*2 − 255.16 × *B*3 + 175.8 × *B*4 − 49.42 × *B*5	0.16
Derived Landsat-8 OLI band reflectance based model[b]	pH = 7.32 + 1.42 × Band 5	0.01
	EC = 422 + 1240 × Band 4 − 3945 × Band 5 + 4217 × Band 6 − 2320 × Band 7	0.05
	OC = 1.12 + 3.72 × Band 3 − 5.56 × Band 4	0.27
	Sand = 52.8 − 168.5 × Band 3 + 316.1 Band 4 − 129.1 × Band 5 − 434.9 × Band 6 + 480.5 × Band 7	0.44
	Silt = 22.54 + 102.21 × Band 3 − 147.35 × Band 4 + 266.63 × Band 6 − 253.86 × Band 7	0.32
	Clay = 23.67 − 45.91 × Band 4 + 251.89 × Band 6 − 252.77 × Band 7	0.44

[a]Derived band reflectance corresponding to IRS-P6 bands of LISS-III, LISS-IV and AWiFS camera: *B*2 = 520–590 nm, *B*3 = 620–680 nm, *B*4 = 770–860 nm, *B*5 = 1550–1700 nm
[b]Derived band reflectance to Landsat-8 OLI bands: Band 3 = 530–590 nm, Band 4 = 640–670 nm, Band 5 = 850–880 nm, Band 6 = 1570–1650 nm, Band 7 = 2110–2290 nm

Developed linear models for estimating soil properties from derived band reflectance corresponding to Landsat OLI bands are also given in Table 1.3. Linear regression models for predicting OC, sand, silt and clay content using derived OLI band data were found satisfactory and even better than using PCs of spectral data and derived IRS-P6 bands. It is interesting to note here that derived band reflectance in SWIR (e.g. Band 6 and 7 of Landsat OLI) has been found as significant inputs to estimate sand, silt and clay contents.

1.10.2.2 Proximally Derived Relationship to Satellite Images

Translating the developed laboratory-derived spectral algorithms for estimating soil properties from remote sensing platform depends on several factors such as the spectral consistency of satellite images, spectral resolution, atmospheric degradation of spectral behaviour, surface roughness, soil moisture content, spatial resolution, the presence of gravels on surface and land surface composition. Such transferability of spectral algorithm was demonstrated by estimating a few soil properties using the OLI band reflectance from the Landsat-8 scene (path: 142, row: 49) of 19 June 2013 (http://earthexplorer.usgs.gov/). The developed linear regression model as presented in Table 1.3 was used as an example algorithm. Estimated

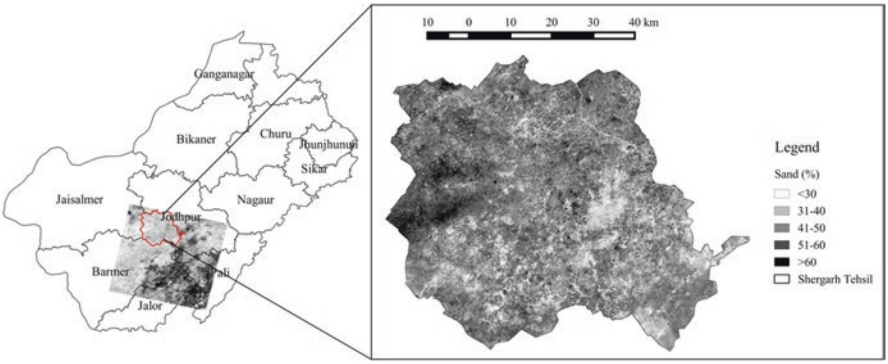

Fig. 1.11 Digital soil map of sand content in Shergarh Tehsil of Jodhpur District in western Rajasthan prepared by using spectrotransfer model involving OLI band reflectance of Landsat-8 as predictor variable (Source: Santra et al. 2015)

sand content for Shergarh Tehsil of Jodhpur district in western Rajasthan using the best algorithm from Table 1.3 is shown in Fig. 1.11. Soil pH and EC could not be satisfactorily predicted from spectral algorithm in the present study although better estimation methods of these soil properties have been reported previously (Shrestha 2006; Lagacherie et al. 2008; Farifteh et al. 2007; Nawar et al. 2014). Most of these reported studies had showed the soil salinity assessment by using Landsat band reflectance or few derived indices such as normalized difference salinity index (NDSI), salinity index (SI) and brightness index (BI).

1.11 Summary

Digital soil mapping (DSM) has been found as an effective tool for representing spatial pattern of soil properties at different scales. This involves geostatistical technique for spatial characterization of soil properties, pedotransfer function approach for modeling the relation among soil properties and 'scorpan' factor approach for relating soil properties with different environmental covariates. The DSM approach is quite different from the conventional soil survey based mapping approach where soil mapping unit represents a polygon in GIS environment and generally indicates a homogeneous landscape unit with single soil property. During last few years, several tools and techniques have been evolved in DSM approach, which needs to be exploited further. Soil information system or soil inference system with digital soil map at the core linked with spatial query builder has been developed at several places of the world. Such operationalization of DSM approach is the present need for true exploitation of the huge effort of creating large soil databases worldwide. Digital soil maps are the key parameters for implementing site-specific management decisions in field. Therefore, it is expected that required soil information will be made available in different IT platforms, e.g. desktop computer, mobile phones, internets, etc., in future and for this purpose suitable strategies need to be formulated.

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2 Will the Traditional Agriculture Pass into Oblivion? Adaptive Remote Sensing Approach in Support of Precision Agriculture

El-Sayed Ewis Omran

Abstract

Is it a time for replacing the traditional agricultural system by adaptive remote sensing (RS)? Yes, of course it is. This chapter has focused on developing four adaptive models to predict and monitor soil-plant properties using RS. First, an image and point spectroscopic model to replace the current soil chemical analysis methods, which are slow, complicated, or inaccurat was developed. Spectroscopy has opened a new era in which outdated conventional soil analyses are being left behind. Spectroscopy can be utilized to precisely predict some soil (e.g. salinity, gypsum, heavy metals) properties, making it an important tool in precision farming.

Second, adaptive and coactive neuro-fuzzy inference system for estimation of difficult-to-measure soil (phosphorus and soil cation exchange capacity, CEC) properties was proposed. The conventional procedures for CEC measurement demand longer time and it is difficult to maintain their stability during long-term experiments.

Third, a real-time adaptive sensor network technology for land degradation prediction was implemented. Advancement in remote sensors and GIS technology has offered an approach to extremely modern early warning systems for observing most environmental hazards. Issuing appropriate warning systems are crucial to alleviate the environmental hazards impact on population, environment, and the economy. Early warning information system (EWIS) can be utilized for the early identification, observing, and prediction of soil salinization, desertification, and water content for farming computerization.

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Finally, adaptive thermal sensing technique to support precision agriculture was suggested. Thermal imaging has shown potential to assist with many aspects of soil and irrigation management. By such methods, thermal information about a large area can be obtained simultaneously and at times see things that otherwise may be hidden. Thermal infrared remote sensing can be used to soil salinity detection, water resources monitoring, and soil surface temperature mapping. This technology is a non-intrusive, non-contact, and non-destructive method used to predict thermal properties of soils.

Keywords
Spectroscopy • Soil-plant analysis • CANFIS model • Data mining • Precision agriculture • Soft computing techniques • Early warning • Thermal infrared

2.1 Introduction

Knowing the value of our land, when the soils are degraded, e.g., through poor land management, the whole civilizations can collapse (Du et al. 2007). It is therefore essential that there are powerful and sensitive tools advanced to investigate soil-plant properties in order to better understand their potential effects on land management. In making resource management decisions, traditional methods have often failed to reach the objectives for complex problems in large systems (Johnson 1999). Outdated soil-plant analysis techniques involve time intensive methods, which get to be constraining when applied at regional or global scales (Du et al. 2008a). A traditional, non-adaptive measurement, is time-consuming, expensive, and must be accomplished in small areas. Therefore, the advancement of alternative tools is needed to analyze the spatial variability of soils inexpensively, rapidly, and accurately and to enable informed policies and land-use decisions (Gmur et al. 2012).

Adaptive management is the paramount approach for tending to this kind of complex issue, which different definitions are available in the literature (e.g., Callicott et al. 1999). Adaptive management acknowledges the fact that management must continue even if not all the information are complete. It views management not only as a way to accomplish objectives, but also as a process of examining to take in more about how the resource or system is being achieved (Johnson 1999). Thus, learning is an inherent objective of adaptive management. As we learn more, we can adjust our strategies to enhance management success and to be more responsive to future conditions.

Three types to measure soil-plant properties can be distinguished (while further classifications are possible): (1) laboratory measurements, (2) proximal sensing measurements, and (3) remote sensing (RS) measurements. The two latter techniques are able to collect spectral data in-situ and are therefore usually exploited to map soil properties (Omran 2012b; Barnes et al. 2003). Proximal sensing may also include handheld measurement, which is used as a fast tool to monitor soil properties in-situ (Stevens et al. 2008). RS has attracted interest among soil scientists as a possible technique for enhancing soil analysis for its rapid, non-destructive, and inexpensive measurements as well as possibilities to determine several soil properties simultaneously (Omran 2012b). RS technique is more efficient when a large number of analyses and samples are required to be examined. This technique is sometimes more straightforward than conventional soil analysis and occasionally more accurate (Brown et al. 2006; Viscarra Rossel et al. 2006). Actually, most of the optical RS means cannot distinguish the entire soil body (pedon). There are many factors (e.g., dust, rust, plowing, particle size distribution, vegetation coverage, and physical and biogenic crusts), which may affect the thin, upper layer that is ultimately detected by optical sensors. Accordingly, optical RS of soils becomes a major challenge. Yet, the upper soil horizon may contain valuable information about the soils, such as soil degradation processes, salinity, organic matter, crust formation, soil moisture, soil runoff, and infiltration, which can be utilized by farmers and decision makers. For all of these applications, single or even multi-band RS means is rather limited and problematic when striving for quantitatively accurate information.

Fuentes et al. (2012) stated that advances in laboratory instrumentation and chemometrics, which extracts information from chemical systems by data-driven means, provide alternatives to traditional methods of conducting soil chemical analysis. Moreover, pedotransfer functions are thus regularly applied to predict difficult-to-measure soil properties (e.g., CEC and phosphorus) from easily measured physico-chemical properties such as texture, organic matter, and pH. Wireless sensor technology is one of the most important point sensing approaches. A diverse range of proximal soil sensing and potential soil morphometrics techniques allows predicting all soil attributes beyond the visible range of the spectrum using non-invasive techniques: x-ray fluorescence, visible/near-infrared (VNIR) spectroscopy, thermal imaging, ground-penetrating radar, and electromagnetic induction (EMI). EMI method (Omran 2012b) has been used to characterize the spatial variability of soil properties accurately. Adaptive RS (spectroscopy and thermal) method can be considered as an alternative tool for soil analysis, especially, when a large number of soil analysis are necessary. Thermal imaging and heat sensing camera have been used for rapid soil, water and evaporation detection (Omran 2012b). So, the question to be answered is: can adaptive remote sensing technique replace soil-plant analysis methods?

As with the adaptive soil management, very little investigation has been done in the area of adaptive RS (for either acquisition or implementation). In terms of adaptive implementation approach, this chapter is geared towards developing four adaptive models to analyze soil and plant using adaptive RS.

2.2 A Real-Time Adaptive Spectroscopic Method to Replace the Current Soil-Plant Analysis Methods

Since soil chemistry became a recognized discipline among the natural science in the middle of the 19th century, chemical soil analysis has become a general routine in the industrialized countries (Hill 2009). For more than 100 years, soil chemists have developed a range of methodologies, based on the soil solutions from extractive procedures. Soil researchers have been challenged and helped by the advancement in strategies, methods, and instrumentation for soil data acquisition and analysis. A prosperity of new soil data has become available; however, some of the information is of rough quality, often outdated, and sometimes wrong (Omran 2012a). To achieve meaningful analysis results, soils should be sampled correctly. The currently utilized traditional soil survey is a complicated, expensive, and time-consuming process. Soil properties are neither stationary nor homogeneous in space and time. Obtaining spatial soil variability analytically in the laboratory is time- and cost-intensive, especially for large-scale applications with high number of soil samples (Borenstein et al. 2006; Du et al. 2007).

Conventional methods of soil analysis based on point sampling and chemical analysis such as inductively coupled plasma (ICP), atomic absorption spectrometry (AAS), or operationally defined sequential extraction can measure physico-chemical data directly, but are time-consuming and relatively expensive and sometimes incorporate the use of environmental damaging chemicals. The traditional soil analysis gives off an impression of being unessential to numerous clients and does not have a market with land managers and policy makers at different scales (Omran 2008). Its high expenses have prevented the introduction of precision agriculture in several parts of the world (Du et al. 2008a). Thus, a reliable and environmentally friendly method is necessary to rapidly detect and analyze soil and to reduce the need for extractions. A developing interest of high-resolution spatial soil data for environmental planning and modeling leads us to research questions: Are the classical tools sufficient to determine accurately the soil and plant properties? Can we obtain new information more efficiently and accurately using sensing tools? Can spectroscopy replaces the out-of-date techniques of soil analysis?

One of the newest and hottest topics in soil-plant analysis today is the spectroscopy. Interests among researchers in the use of visible-near infrared (VNIR) reflectance spectroscopy in soil science have increased over the past few years (Stenberg et al. 2010; Omran 2016a). Reflectance spectroscopy is relatively less expensive and faster than traditional wet chemical measurements (Summers 2009). Spectroscopy in VNIR region has been used to rapidly analyze and monitor soil constituents both conveniently and accurately. It is a promising tool for the detection and analyzes soil in the spectral range 400–2500 nm, which can be used due to the presence of strong spectral features attributable to soil components in this region (Ben-Dor et al. 2009; Minasny et al. 2009).

2.2.1 Rapid and Low-Cost Determination of Soil Properties Using Spectroscopy

2.2.1.1 Point Spectroscopy

A ground-based approach defines the soil profile by a penetrating optical spectroscopy (POS), analytical spectral devices (ASD spectrometer), and near-infrared reflectance spectroscopy (NIRS). The POS may substitute the wet laboratory measurements and the subjective field observation. Instead of describing the profile in the field and sending soil samples to the laboratory, the POS approach with NIRS analysis enables in-situ soil profile recognition rapidly and effectively. Transmittance and diffuse reflectance (DRIFT) spectroscopy in the mid-infrared range is well-established methods for soil analysis. Extra mid-infrared techniques have been studied, and in particular: attenuated total reflectance (ATR), which is commonly used for analysis of liquids and powders for which simple transmittance measurements are not possible (Linker and Shaviv 2009) and secondly is the Fourier transform infrared (FTIR) spectrometer, which is based on determination of ion concentration, using ion-exchange membranes. Third, the FTIR-ATR technique that has been successfully applied to soil analysis as well as to determine the nitrate concentration (Linker et al. 2005, 2006; Borenstein et al. 2006; Jahn et al. 2006). It is conceivable to distinguish between ^{14}N and ^{15}N in such spectra, which opens very promising opportunities for investigating nitrogen transformation in soils (Linker and Shaviv 2009). Finally, photo acoustic spectroscopy (PAS), which is based on absorption-induced heating of the sample produces pressure variations in a surrounding gas. These fluctuations are recorded and create the PAS signal. Point spectroscopy has been applied successfully to the quantitative determination of soil properties such as available nitrogen, phosphorus and potassium, organic matter, calcium carbonate, soil salinity, and heavy metals (Du et al. 2007, 2008a, b; Nawar et al. 2014; Omran 2016a).

2.2.1.2 Spatial Imaging Spectroscopy

An airborne and satellite-based approach depicts the soil surface by imaging spectroscopy (IS) innovation. The IS approach serves as a suitable method that might supplant the outdated, ancient air photo method, providing cognitive and quantitative spatial views of the areas in question. IS conveys a new measurement in the field of remote sensing by increasing the envelope of point spectrometry to the spatial domain. It delivers a tangible outlook by adding spatial detail to spectral information, thereby improving the thematic application of spectral recognition algorithms. This ability exists for both far and close distances, such as data acquired by satellites or by microscopic sensors, respectively.

Hyperspectral images are characterized by imaging and spectroscopic property, which distinguishes the terrestrial features into the unique spectral signature. This property is valuable in prediction of soil physico-chemical and mineralogical properties. Hyperspectral sensors, measuring hundreds of both spatially and spectrally contiguous images, provide unique spatial/spectral datasets for soil chemical and mineralogical analysis (Omran 2015, 2017). Hyperspectral bands have a comprehensive spectral pattern of each pixel, which can be derived for target detection, discrimination, and classification the objects (Zadeh et al. 2013) with great precision and detail. IS provides detailed spectral signatures for every pixel. These signatures offer enough information to identify and quantify the materials that might be present within a single pixel (Gomez 2000). Hence, hyperspectral bands offer a vastly enhanced ability to classify the objects in the scene based on their spectral properties (Plaza et al. 2009). IS, working in the visible (400–700 nm), near-infrared (700–1300 nm), and short-wave infrared (1300–2500 nm) ranges, offers the possibility to directly predict soil physico-chemical and mineralogical properties (Omran 2015, 2017).

Therefore, the author suggests combining between spectral-based (prediction) approach and pedotransfer functions (inferred) approach to replace the conventional soil analysis process.

2.2.2 Spectroscopy to Predict Soil and Plant Properties

A diagram of the principle steps in the procedure to predict some soil properties (e.g., clay, iron oxides, salinity, calcium carbonate, organic matter, heavy metals) from soil sampling preparation to prediction is presented in Fig. 2.1 (upper). The process is used to collect soil spectra in the field and laboratory. The overall procedures for using spectroscopy in soil analyses consist of three steps: soil sample preparation and spectral measurement; pre-processing; and model building and validation. Soil reflectance spectra are collected utilizing a portable spectroradiometer (FieldSpec-Pro, Analytical Spectral Devices), which measures reflectance over a range from 350 to 2500 nm with a resolution of approximately 10 nm and sampling interval of 3 nm (Fig. 2.1, lower).

The spectral measurements are conducted in a dark laboratory environment to avoid contamination by stray light. Plastic dishes are used to contain the soil samples, which were smoothed off to a thickness of 2.0 cm (Mouazen et al. 2007). Soil samples are illuminated with halogen lamp positioned in the same plane, under a 45° illumination angle and from a distance of 20 cm. To measure each sample's spectral reflectance, the soil samples are measured with a viewing angle of 30° from the nadir at a distance of 15 cm. The reflected radiance from a white reference panel with a known reflectance is recorded before scanning each sample. To calculate the absolute reflectance of the samples, the radiance from each sample is divided by the radiance from the white reference panel and multiplied by the reflectance of the reference panel.

To reduce noise and enhance the absorption frequencies, some spectral pre-processing techniques have to be performed (Naes et al. 2004) to remove any irrelevant information. Based on Beer-Lambert law, the measured reflectance (R) spectra have to be transformed in absorbance through log ($1/R$) to enhance the linearity between measured absorbance and soil properties. The absorbance spectra are smoothed using a Savitzky–Golay filter algorithm with a first derivative to remove an additive baseline (Weng et al. 2008). However, direct quantitative prediction of soil characteristics is almost impossible because soil constituents interact in a complex way to produce a given spectrum. Therefore, quantitative soil spectral analysis requires statistical models such as multiple linear-regression (MLR), principal component regression (PCR), and partial least squares regression (PLSR). Chemometrics are prerequisite to extract the information about the quality attributes that is hidden within the spectral information (Rossel and Behrens 2010; Stenberg et al. 2010). To relate the soil spectrum to soil attributes, i.e., continuum removal (CR) and PLSR have to be used. The performance of the models is usually high and explains more than 80% of the variance (Weng et al. 2008).

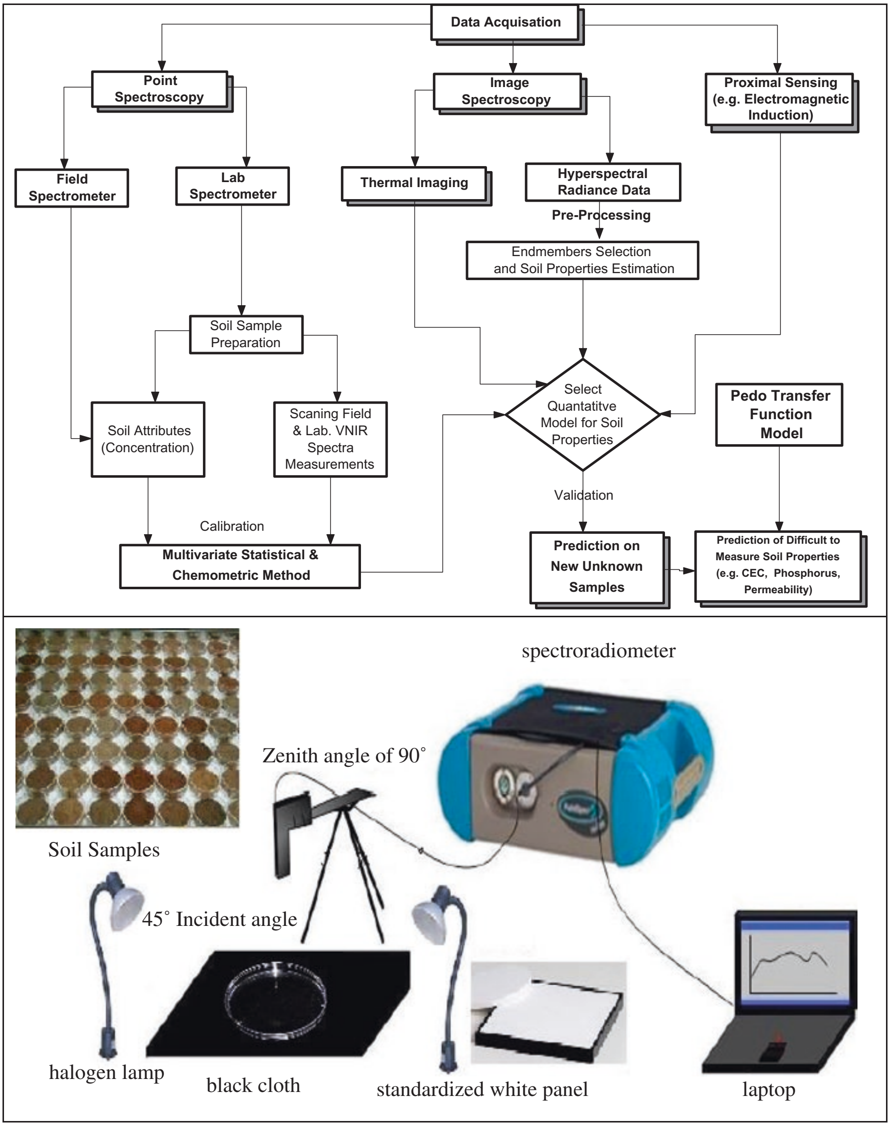

Fig. 2.1 Overall procedure for rapid and low-cost determination of soil properties (*upper*) and FieldSpec-Pro spectroradiometer (*lower*) for soil analyses

2.2.3 Interpretation of Spectral Signatures of Bahr El Baqar Soils

To evaluate the effectiveness of spectroscopy for prediction some soil properties, 35 soil samples gathered from the Bahr El Baqar region, Egypt were scanned in the 350–2500 nm region. Clay, iron oxides, salinity, calcium carbonate, organic matter, and heavy metals are the most important soil constituents. Partial least squares regression (PLSR) was implemented to develop calibration models, which were independently tested for the predictions of soil properties from the soil spectra (Omran 2016a).

Figure 2.2 displays the main characteristic spectral signatures and corresponding soil attributes and provides selected major spectral regions for some scanned soil properties. Some samples have high clay minerals, and other samples have calcite and iron oxides. All plotted spectra show a typical soil reflectance shape in each region of the wavelength domain. Reflectance is usually lower in the visible range (350–650 nm) and higher in the near infrared with specific absorbance bands around 1400, 1900, and 2200 nm.

The predictive capacity of reflectance spectroscopy and PLSR was high for the soil salinity and clay content. These results can be explained by the strong spectral activity of organic carbon and clay in the VNIR-SWIR region. The accuracy of the models is low indicating the need of improving the measurement protocol to achieve more reliable data, and to test other pre-processing and modeling methods as well.

The wavelengths used in the clay minerals prediction were between 890 and 2430 nm, and all relate to the soil's mineralogy. Absorptions between 400 and 1000 nm are caused by the iron oxides present, mainly hematite and goethite, those between 1300 and 1500 nm are from absorption by hydroxyl groups in clay minerals and water. Absorptions between 1700 and 1800 nm are produced by carbon. The strong absorption near 1900 nm is due to water (hygroscopic water and water held within clay mineral structures). Absorptions between 2100 and 2500 nm are caused by the clay minerals (kaolinite, illite, and smectite), carbonates, and organic compounds. The optimal estimation models of two types of clay mineral contents using specific wavelengths revealed that the recovery accuracy was acceptable. Therefore, the reflectance spectra of soil acquired from Bahr El Baqar could be used for estimation of salinity, calcite, iron oxides, and clay minerals (illite and montmorillonite) in the soils.

A likely relationship between the heavy metal concentrations and reflectance spectra (Fig. 2.2) was determined for the samples. The spectral signatures of the soil samples changed significantly as a function of heavy metals concentration. It was hypothesized that the samples with the highest concentrations would have the lowest reflectance, and that the reflectance would increase proportionally as the heavy metal concentrations decreased.

2.2.4 Overall Advantages and Disadvantages of Spectroscopy

Soil reflectance spectroscopy is a system to measure soil properties quickly and quantitatively in both point (spectroscopy) and spatial (imaging spectroscopy) domains. The many advantages of NIRS in comparison to other spectral methods include (Du et al. 2008a): several soil physico-chemical and mineralogical properties can be determined simultaneously; no special qualification for performing analysis is needed; rapid scans (analysis of one sample in about 1 min), no reagents are

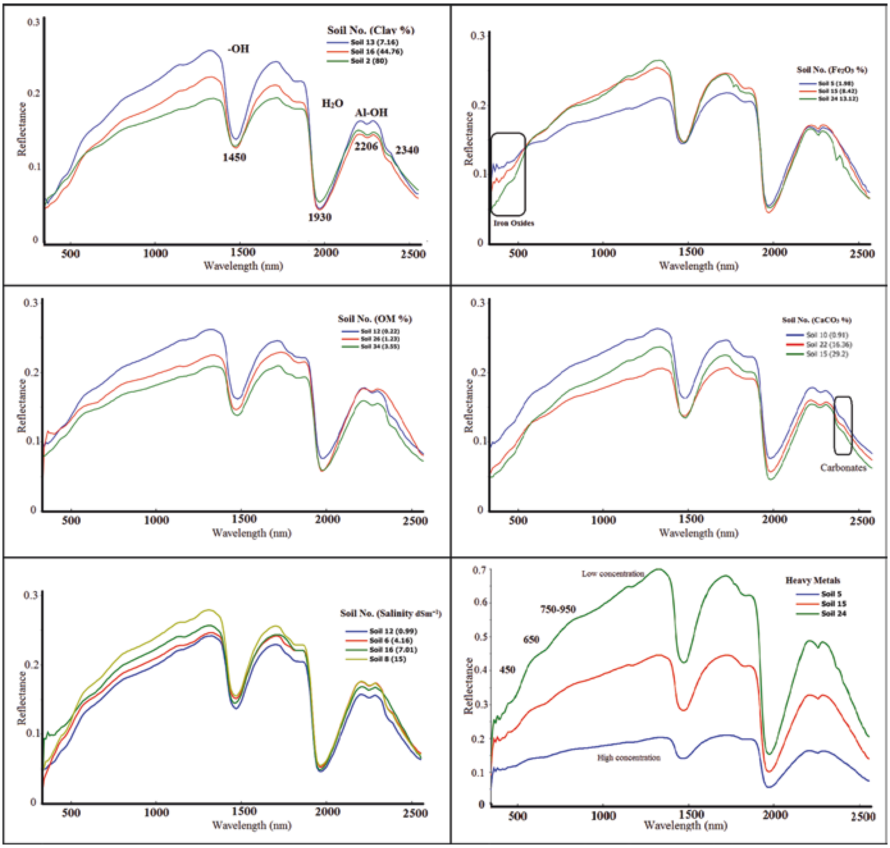

Fig. 2.2 Reflectance spectra of some soil samples collected from Bahr El-Baqar region indicating the spectral features of the most important constitutes (iron oxides, clay minerals, salinity, carbonate minerals, organic matter, and heavy metals)

required, and no hazardous chemicals needed; minimal sample preparation; non-destructive nature of the method; lower staff requirements; and potentially very accurate results. Moreover, this approach may allow gathering of information in real time with sensors fixed in agricultural fields. So, the proposed approach also closes an obvious gap in the pedological toolkit because so far profile descriptions were just that descriptions.

However, there are some disadvantages of IS for soil analysis. Although atmospheric attenuation is one of the main problems in the IS domain, it plays a central role in soil IS applications. This is because if not correctly completed, signals not related to soil chromophores (mostly clay and iron oxides; organic matter; and water), which is a substance that responsible for its color (Ben-Dor 2002) might be incorrectly classified. Whereas in multi-spectral RS, this problem is rather negligible (wide Full Width at Half Maximum, FWHM, bands that are situated on atmospheric windows). In IS, this is more challenging because the contiguous spectral channels (with narrow FHWM) covering absorption features of atmospheric gases. Since the spectral features of soils are relatively weak, narrow, and mixed, a favorable atmospheric correction is required. The IS means are characterized by lower signal-to-noise ratios than the point spectrometry offers. In addition, the soil surface is not always flat, smooth, or homogenous and therefore sample preparation (as is done in the lab) is difficult. This leads to problems such as variations in particle size, and bidirectional reflectance distribution function effects.

2.3 Adaptive Rapid Integrative CANFIS Model for Estimation Difficult-to-Measure Soil Properties (e.g., CEC and Phosphorus)

One of the most significant soil parameters is the cation exchange capacity (CEC), which is considered as an excellent indicator of soil physico-chemical characteristics and precision agriculture as well (Ghaemi et al. 2013). Cation exchange is crucial for measuring fertility, nutrient retention capacity, and the ability to protect groundwater from contamination. CEC is a common indicator of soil condition or vulnerability. Soil CEC is directly measured using the ammonium acetate method that is difficult, time-consuming, and expensive. Accurate estimation of CEC value depends upon organic matter content, mineral type, soil type, and soil pH. High lime content in arid and semi-arid region is also a major problem for accurate CEC estimation (Minasny and McBratney 2002) because of the presence of large amounts of calcium carbonate. The inability to obtain soil CEC rapidly and inexpensively remains one of the biggest limitations of precision agriculture (Omran 2012b). Therefore, innovative methods for CEC prediction would be quite welcome.

The soft computing technique is one of the hottest topics in soil resource inventory, which may be used in achieving tractability, robustness, and to offer a low-cost solution with a tolerance of imprecision, uncertainty, partial truth, and approximation. Data mining (DM) and adaptive neuro-fuzzy inference system are examples of such techniques. DM is the most recent advancement in science and technology. It has a high potential for building meaningful patterns, algorithms, and procedures from databases. Along with exploration of existing knowledge, this technique also enables to discover hidden structures, proportions, patterns, symptoms, and relationships (Ghorbani et al. 2010). DM algorithms have become available as alternatives, which automatically develop equations from the information contained in the datasets (Cabena et al. 1998).

Multiple regressions, artificial neural networks (ANN), and adaptive neuro-fuzzy inference system (ANFIS) are the three common methods used to estimate soil physico-chemical characteristics. In contrast to extensive applications of conventional regression models to predict difficult-to-measure soil properties indirectly from other data, coactive neuro-fuzzy inference system (CANFIS) has not been extensively exploited for this purpose, although they have presented much potential in related applications (Azamathulla et al. 2009; Bocco et al. 2010; Gago et al. 2010;

Huang et al. 2010; Kisi et al. 2009). The objective of this part is to develop a rapid and applicable CANFIS data-mining model for the estimation of difficult-to-measure soil properties.

2.3.1 Artificial Neural Networks

Artificial neural networks (ANNs) have been used successfully in the prediction of several difficult-to-measure soil (phosphorus and CEC) characteristics (Merdun et al. 2006; Keshavarzi et al. 2015). In comparison to conventional models, the ANN does not require specific function determination to express the relationship between input and output variables (Schaap and Bouten 1996). One such type of ANNs is a multilayer perceptron (MLP) network, which uses an error back-propagation training algorithm and is applicable to develop neural network transfer functions (Sunil et al. 2008). However, the change in soil condition with the passage of time and uncertainty in data can be frustrating.

ANNs are computing systems made up of a number of simple, highly interrelated processing elements, also named neurons. An ANN is made of an input layer, one or several hidden layers, and an output layer of neurons (Tracey et al. 2011). The input layer neurons collect the input information from the external environment and convey it to a hidden layer. Every neuron of a subsequent layer first computes a linear combination of the outputs from all neurons of the preceding layer and then adds a bias to it. Furthermore, each neuron of hidden layers applies an explicit nonlinear function, called activation function, to this linear combination plus bias. The coefficients of the linear combinations and the biases are called weights (Bocco et al. 2010; Sobhani et al. 2010; Turan et al. 2011).

2.3.2 Adaptive Neuro-Fuzzy Inference System

ANFIS uses the learning capability of ANNs to derive fuzzy rules with appropriate fuzzy set membership functions (Enayatifar et al. 2013; Mohandes et al. 2011; Ata et al. 2010). The main strength of ANFIS in comparison with ANNs is that it generates linguistically interpretable IF–THEN rules (Sobhani et al. 2010). ANFIS models capture the relationship between input and output data by establishing fuzzy language rules, while ANNs do so in the form of trained connection weights. ANFIS shows very good prediction capabilities, which makes it an efficient tool to deal with encountered uncertainties in any system. ANFIS, as a hybrid intelligent system that enhances the ability to automatically learn and adapt, was used by researchers in various systems (Shamshirband et al. 2013; Singh et al. 2012; Petković and Ćojbašić 2012). So far, there are many studies on the application of ANFIS for estimation and real-time identification of many different systems (Kurnaz et al. 2010; Petković et al. 2012; Ekici and Aksoy 2011). Furthermore, it is reported that constructing an ANFIS model is less time-consuming than an ANN model (Azamathulla et al. 2009).

2.3.3 Prediction of Soil CEC Using CANFIS Model

Coactive neuro-fuzzy inference system (CANFIS) structure used is similar to ANFIS model and was introduced by Jang et al. (1997). The foundation of CANFIS is the data driven from fuzzy modeling approach, which allows for the model extraction from the input/output data represented as fuzzy inference system (Mogaji et al. 2014). This model runs a Sugeno fuzzy system on neural network architecture and for the training process. It uses error back-propagation training method and least squares error. CANFIS is a multilayer network model that uses progressive learning algorithms of artificial neural networks and fuzzy logic to describe the entrance to an exit (Firat and Gungor 2007). In addition, CANFIS allows the extraction of fuzzy rules from numerical and professional data and creates the basic and fundamental rules appropriately (Iqbal et al. 2014). CANFIS offers the learning ability of neural networks to define and utilize the relationship between input–output variables and using fuzzy rules, the structure of the system entrance can be established.

One of the most important stages in the CANFIS model development is finding out the optimum number of neurons in the hidden layer. High number of hidden units can lead to overestimation, while a smaller number causes underestimation. Therefore, trial and error method has to be used in order to find out the optimal number of hidden neurons. In the structure of CANFIS, fuzzy sets can be used as weight connections. Input and output variables could be interpreted as neurons and the learning algorithms reform structure parameters, or both. Figure 2.3 shows the CANFIS model used to predict difficult-to-measure soil properties.

The fuzzy IF-THEN rules of Takagi and Sugeno (Tagaki and Sugeno 1985) and inputs for the prediction difficult-to-measure soil properties could be presented as follows:

$$\text{if } x \text{ is } A \text{ } \textit{and} \text{ } y \text{ is } C \text{ then } {}_1 = p_1x + q_1y + r_1 \tag{2.1}$$

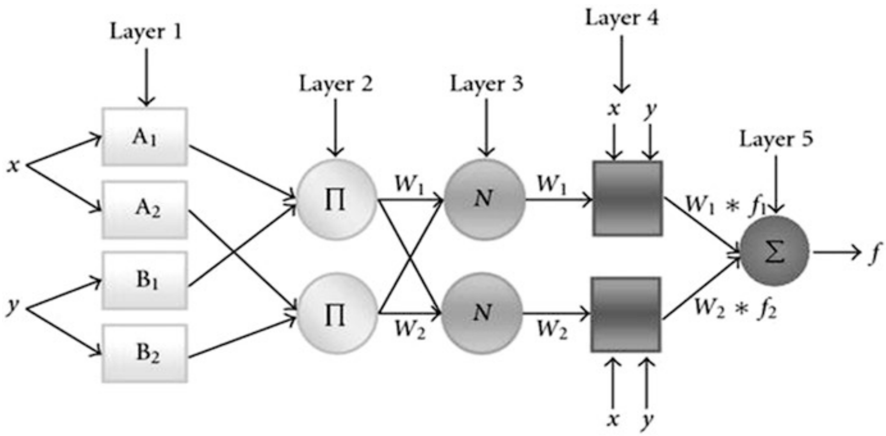

Fig. 2.3 CANFIS model structure

CANFIS model consists of five layers. The first layer is made up of input parameters (clay, organic carbon, satellite bands, pH), and it delivers the input values to the accompanying layer. Each node here is viewed as an adaptive node having a node function 0 = $\mu_{CD}(x)$ and 0 = $\mu_{AB}(x)$ where $\mu_{AB}(x)$ and $\mu_{CD}(x)$ are membership functions. Bell-shaped membership functions having the maximum value (1.0) and the minimum value (0.0) are chosen, such as,

$$\mu(x) = \text{bell}(x;\, a_i, b_i, c_i, d_i) = \frac{1}{1 + \left[\left(\dfrac{x - c_i}{a_i}\right)^2\right]^{b_i}} \tag{2.2}$$

where {*ai*, *bi*, *ci*, *di*} is the arrangement of parameters set. The parameters of this layer are assigned as premise parameters. Here, *x* and *y* are the inputs to nodes.

The membership layer is the second layer, which searches for the weights of every membership function. This layer gets the receiving signals from the previous layer. It performs as a membership function to the representation of the fuzzy sets of each input variable, respectively. The layer acts as a multiplier for the getting signals and conveys the result in $wi = \mu_{AB}(x) * \mu_{CD}(y)$ form. Every output node displays the firing strength of a rule.

The third is known as the rule layer. All neurons here go about as the precondition matching the fuzzy rules, i.e., each rule's activation level is calculated whereby the number of fuzzy rules is equal to the quantity of layers. Every node calculates the standardized weights. Each of the nodes computes the value of the rule's firing strength over the sum of all rules' firing strengths in the form of $w_i^* = \dfrac{w_i}{w_1 + w_2}$, i = 1 , 2. The outcomes are referred to as the normalized firing strengths.

The fourth layer, which known as the defuzzification layer, is in charge of giving the output values because of the inference of rules. Every fourth layer node is an adaptive node having the node function $o_i^4 = w_i^* xf = w_i^*(p_i x + q_i y + r_i)$. In this layer, the {*pi*, *qi*, *r*} is the variable set. The variable set is chosen as the consequent parameters. In order to optimize the CANFIS model, it was necessary that a basic parameter of the first layer and the resulting parameter must be defined in the fourth layer.

The final layer is known as the output layer (e.g., CEC, phosphorus). It includes all the getting input from the previous layer. Thereafter, it changes over the fuzzy classification outcomes into a binary (crisp). This node calculates the total output as the wholesum of all receiving signals.

$$O_i^5 = \sum_i w_i^* xf = \frac{\sum_i w_i f}{\sum_i w_i} \tag{2.3}$$

2.3.4 Soil Phosphorus Prediction Using Multi-Objective Group Method of Data Handling (mGMDH)

As a direct estimation of soil phosphorus (P) at large scales is dull and expensive, pedotransfer functions (PTFs) have been produced to describe soil P (Keshavarzi et al. 2015). Artificial neural networks (ANNs) are utilized to model the complex interaction of the environmental systems without requiring the explicit formulation of the relationships that may exist between variables (Omran 2012b). ANNs are effectively applied for the estimation of some difficult-to-measure soil characteristics (Keshavarzi et al. 2015) using multivariate regression models. However, the models developed for one region may not provide a good estimation for different territories (Wagner et al. 2001). Therefore, the utilization of ANNs prompts effective use of different types of algorithm in which group method of data handling (GMDH) algorithm is one.

The GMDH process is a self-organizing methodology by which step by step convoluted models are produced taking into account the assessment of their performances on a set of multi-input single-output data pairs. Along with ANNs and genetic programming (GP), GMDH is a data-driven technique appropriate for automatic generation of models linking the input and output variables. The central considered GMDH is to build a logical function in a feed forward network based on a quadratic node transfer function (Farlow 1984) whose coefficients are to be obtained using a regression technique. The technique chooses automatically the essential input variables and constructs a hierarchical, polynomial regression given a degree of complexity specified by the user. Uniquely in contrast to ANNs techniques, which are basically deductive in their nature, the GMDH method, as GP, does not require an arbitrary, a priori structure of the network connecting inputs and outputs. The structure of the model and the dependence of outputs on the most critical inputs are found producing a network structure based on the characteristics of the dataset during the estimation process itself. The GMDH networks can then be considered universal structure identifications (Ungaro et al. 2014).

Pachepsky et al. (1998), pioneers of utilizing GMDH in soil science, established point PTFs from data on soil texture, bulk density, penetration resistance, and water content at different suction values to predict the soil water retention curve (SWRC). Different researchers have been developing PTFs by ANNs and GMDH to measure water content at various matric suctions from simple to quantify soil physical properties (Ungaro et al. 2005; Ghanbarian-Alavijeh and Hunt 2012; Neyshaburi et al. 2015). They found that GMDH-driven point PTFs performed better except for water content at 1500 kPa. Using of multi-objective group method of data handling (mGMDH) in the PTFs estimation has not yet been commonly used to predict available soil phosphorus (ASP). The goal of this part is to show the potential of mGMDH in the PTFs development and estimation of ASP.

Based on an easy-to-measure soil properties, the mGMDH was utilized for the prediction and modeling of ASP. The soil properties used are soil organic carbon (OC), calcium carbonate equivalent (CCE), and pH. In this methodology, GMDH was utilized to avoid the trouble of knowing from the earlier knowledge of the mathematical model of the process being considered. Subsequently, it can be utilized to model complex systems without having a particular knowledge of the systems (Neyshaburi et al. 2015). A model can be represented as an arrangement of neurons at which diverse sets in every layer are linked through a quadratic polynomial and, thus, deliver new neurons in the next layer. Such description can be utilized as a part of modeling to connect inputs to outputs. The formal meaning of the identification problem is to find an inexact relationship between a set of input variables (x_1, x_2, x_3,…, xn) and an output variable Y. Therefore, the mathematical description can be completely represented by a system of partial quadratic polynomials (Eq. 2.4):

$$Y = a_0 + a_1 x_i + a_2 x_j + a_3 x_i x_j + a_4 x_i^{\ 2} + a_5 x_j^{\ 2} \tag{2.4}$$

where a_1, a_2,…, am … are vectors of parameters. Comprising of just two variables (neurons) that predict output Y for a given arrangement of input variables (x_1, x_2, x_3,…, xn) as close as could reasonably be expected to its real value Y. A comprehensive synopsis of mGMDH algorithms was given by Atashkari et al. (2005). GMDH decomposes the unpredictability of a procedure into numerous simpler relationships each described by low order polynomials (2) for every pair of the input values. Typical GMDH network maps a vector input x to a scalar output Y. Every neuron of the polynomial network fits its output to the desired value Y for each input vector x from the training set. It describes an ideal structure of complex system model with recognizing nonlinear relations between input and output variables.

Multi-objective optimization, multicriteria, or vector optimization was utilized as a vector finding of choice variables fulfilling constraints to give satisfactory values for all of the objective functions (Coello Coello and Christiansen 2000). In such optimizations, there are several objectives or cost functions (i.e., a vector of objectives), which ought to be optimized at the same time. The improvement of the objective functions has been frequently at the expense of each other; one objective function enhances, another deteriorates. Therefore, there is no single arrangement that fulfills all of the objective functions. Due to its capability and better performance, it was concluded that mGMDH is recommended for the estimation of ASP.

2.4 Adaptive Early Warning Information System to Mitigate the Climate Change Hazards

Climate change is no more an illusion. Its impact is a globally witnessed and interventions must be highly addressed at international, regional, and national levels. Climate change is an overarching driver affecting numerous soil threat issues (Gleditsch 2012). Waterlogged area, which is an environmental issue, is found throughout the world (Quan et al. 2010; Qureshi et al. 2008; Minar et al. 2013; Chowdary et al. 2008). Waterlogging is causing major problems affecting many hectares of land and influencing the soil, as well as causing pollution to water bodies. Governments have to effectively respond to these dangers going for minimizing the rate of this change and raising the adaptability to local communities to adapt to its devastating impact on socio-economic advancement. Monitoring and predicting these threats and issuing timely warning systems is essential to alleviate their disastrous effect on population, environment, and the economy (Ashraf et al. 2014).

The early warning system (EWS) is aimed at tracking changes as "early" as possible. Early warning defined the way towards identifying a possible hazard utilizing prediction modeling and experts and warning crisis managers and decision makers (Grasso 2005, 2012). These models utilize the real conditions and predictions, which brings about expected threats, with an edge of vulnerability (Jonkman 2007; van Noortwijk and Barendregt 2004). When these predictions surpass pre-defined warning or security level, alerts will be generated and emergency (Ministry of Transport PWAWM 2008; Kolen et al. 2009) organizations will be put into place. Early warnings permit the organization to adapt early, forward-thinking change strategies, in order to gain competitive benefits. The main objective of this part is to actualize an effective early warning information system (EWIS) to assist soil surveys for precision agriculture.

2.4.1 An EWIS for Land Degradation Prediction

Land degradation is an expanding issue all around, exacerbated by climate change and influencing food security, threatening water resources, and at last acting as a driver of migration (ELD 2015). Land degradation keeps on being the major contributing factor in most national devastating disasters, particularly related to salinity, water table rising, erosion, drought, and desertification. There is, therefore, the need to monitor and early predict such patterns to diminish associated impacts. Early warning information system (EWIS) for land degradation is centered on producing risk/vulnerability maps and early warnings of potential trends in these threats.

The obtaining of baseline data for the EWIS setup such as current land-use/cover, topographical map, soil, and rainfall information is vital. Such data would then be utilized for simulation and modeling for input into the EWIS. It is critical that spatial and non-spatial data on all affected areas be captured at the same specific time when changes occur in a very systematic and reliable way. The common trend for data collection and monitoring is by the utilization of earth observation (EO) technologies. Such EO data are then combined with socio-economic data and other multidisciplinary components of EWISs. The utilization of polarimetric synthetic aperture radar (SAR) and hyperspectral sensors with multiple sensors allows for the combination of different spatial, temporal, spectral, and radiometric resolutions to (1) recognize trends and find vulnerable areas (small-scale monitoring), and (2) evaluate vulnerability and predict possible situations (large-scale mapping) (Holecz et al. 2003). Most commonly utilized coarse resolution satellite systems for regional/global land degradation related environmental monitoring include NOAA's AVHRR, GOES, and MODIS sensors as well as ESA's ENVISAT and METEOSAT systems. However, most moderate- to high-resolution optical data include Landsat series

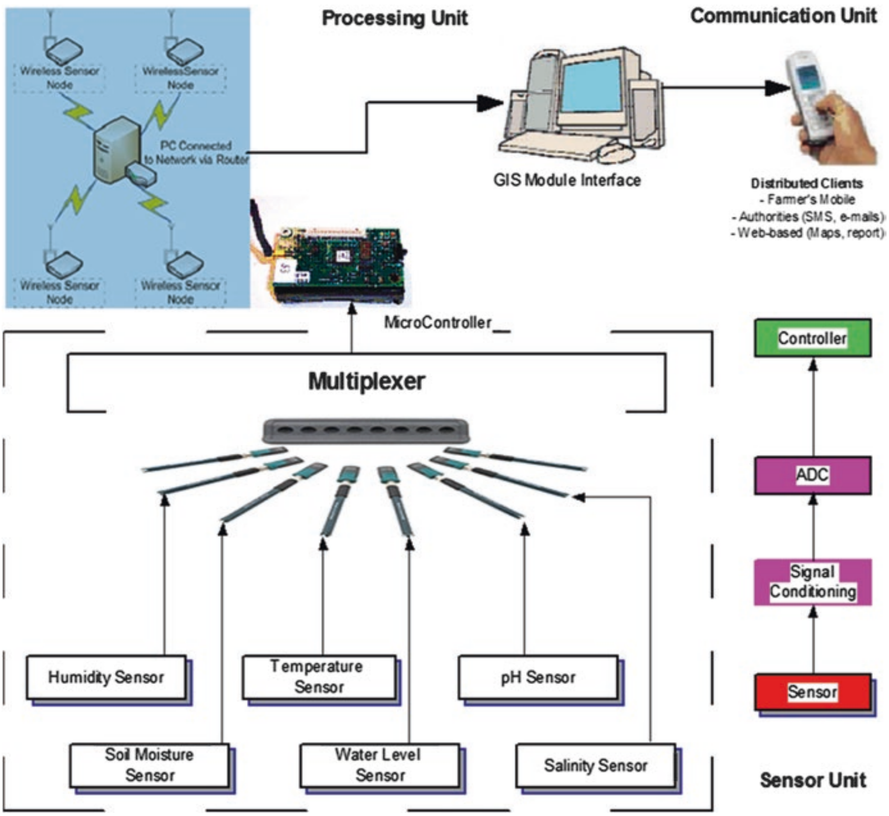

Fig. 2.4 An adaptive wireless sensor network, WiFi, and sensor node to support early warning information system (EWIS) for land degradation prediction

(MSS, TM, and ETM+, landsat-8), SPOT series (SPOT-4 and -5), and IRS's P4&1C satellite series (IRS-WiFS and IRS-LISS).

Figure 2.4 demonstrates the concept of wireless sensor network, WiFi, and sensor node used for land degradation prediction. Different wireless sensors can be utilized for detecting distinctive land degradation hazards, particularly identified with salinization, pH, soil moisture, water table rising, erosion, drought, and desertification. The sensor will produce the signals, which should be transmitted to the managers through low-cost communication devices. It needs low power and less maintenance, which can operate on a wireless architecture. A wireless sensor network (WSN) is spatially distributed autonomous sensors to monitor land degradation hazards and to helpfully pass their information through the network to a principle area.

From an implementation point of view, sensor nodes are placed under the control of WSN. The base station is stationary and it collects the data from sensor nodes. The controller makes responsibilities, processes data, and controls the usefulness of different components in the sensor node. Sensors are hardware devices that produce a measurable response to a change in a physical condition such as water level, soil moisture, and temperature (Fig. 2.4). The continual analog signal produced by the sensors is digitized by an analog-to-digital converter and sent to controllers for further processing. A sensor node ought to be small, consume extremely low energy, work in high volumetric densities, be self-governing and work unattended, and be versatile to the environment. Different wireless standards have been setup. Among them, the standards for wireless LAN, IEEE 802.11b ("WiFi") (IEEE 1999b) and wireless PAN, IEEE 802.15.1 (Bluetooth) (IEEE 2002) and IEEE 802.15.4 (ZigBee) (IEEE 2003), are utilized more widely for programming and computerization applications. An 802.11 (WiFi) mesh network comprised of high-end nodes, such as gateway units (Fig. 2.4).

2.4.2 Adaptive Wireless Sensor Technology for Precision Agriculture Applications

Date palm, *Phoenix dactylifera L.* (*Arecaceae*), is one of the earliest plants that had been cultivated for its fruit for at least 5000 years BC (Khalid et al. 2011) and most important fruit trees cultivated in the Middle East and North Africa including Egypt (Sawaya 2000). One of the major threats to *dactylifera* over the world is the red palm weevil (RPW), *Rhynchophorus ferrugineus* (Olivier), (Coleoptera: Curculionidae) (Dembilio et al. 2009). RPW is an economically important invasive tissue borer that has a broad host range restricted to palm trees, mostly young trees less than 20 years old. Early detection and control timing of RPW is an important topic to avoid the extensive damage to palm trees, as well as the emergence and migration of adult weevils (Faleiro 2006). The early prediction of insect pests helps the farmers to avoid heavy sprays of pesticides and take the necessary actions to restrict dangerous infestations (Yones et al. 2012). Early warning of this pest may represent the only way to setup efficient actions to fight the coleopteron in trees where it takes over, thus limiting its spreading in contiguous palms.

The most common method of RPW testing is the visual detection (Mahmud et al. 2015). There is no reliable gadget to detect infestation in the field (Nakash et al. 2000). Since direct visual detection of the RPW is quite difficult (Faleiro 2005), alternative detection methods are needed. There is a need to develop a system that can replace traditional techniques. Therefore, the objective of this part is to propose an early warning system (portable and automatically) to detect the presence of RPW along with its larva by sensing its (sound and heat) activity in offshoots.

Four stages for RPW detection: sound acquisition, digitalization, audio analysis, and transmission of results. Figure 2.5 shows the main components of the proposed sensor architecture, which consists of two parts. The first part consists of: (1) an audio probe, responsible for securing of sounds from the RPW, conditioning and legitimately enhancing the caught sound signal, making it reasonable to be master processed by the detection sensor. (2) A low-power processor and supply that will have the capacity to run and process the sound taken by the audio probe and decide

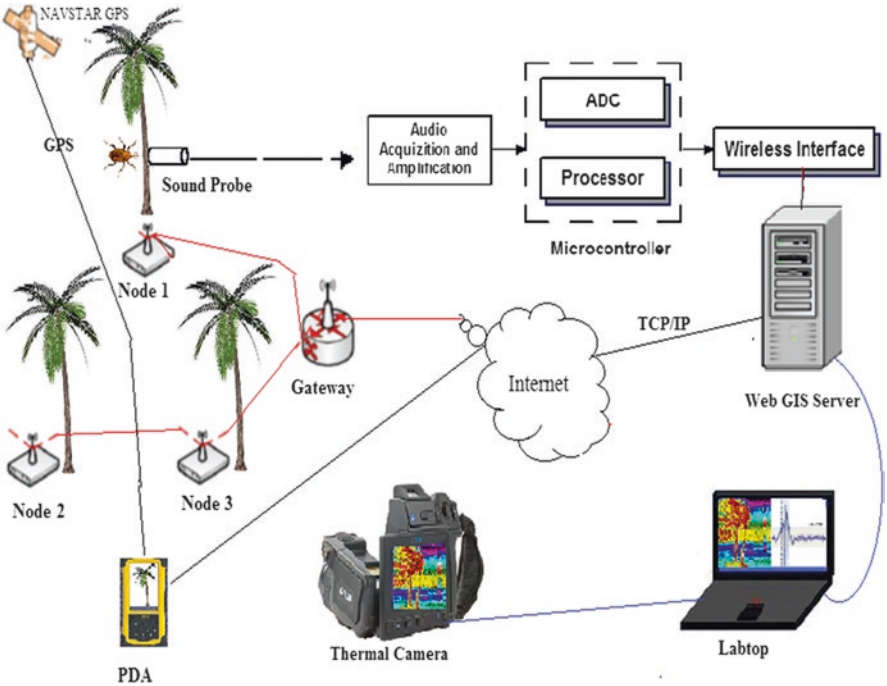

Fig. 2.5 A prototype diagram for the suggested red palm weevil (RPW) detection system

the RPW presence. (3) A wireless communication interface, ready to convey messages reporting the results of RPW activity.

The sound probe delivers the signal caught from the palm tree with the highest possible quality. The sound probe is made out of three components: the microphone, the probe, and the signal conditioning stage. The weight and size of the sensor must be sufficiently small to be fixed on the palm tree. With reference to the audio acquisition task, the analog-to-digital converter (ADC) was used. The audio implementation should be done utilizing the on-chip ADC of the microcontroller to digitalize the audio. The benefit of this option is that parameters and power consumption of the amplification stage may be fine-grain designed, so this approach has chosen to utilize in the selected sensor. A wireless microphone contains a radio transmitter. It transmits the audio as a radio rather than via a cable. It sends its signal using a small FM radio transmitter to a nearby receiver connected to the sound system. The radio interface is up to make a dependable point-to-point outdoor communication over distances of 30 m.

The second part of the system was to examine the ability to detect infected trees using thermal images. The hypothesis was that the tunneling of RPW destroys the vascular system of the palm and creates local conditions of water stress. Mozib and El-Shafie (2013) confirm that the average temperature of the infested date palm was significantly higher (32.60 °C) than the average temperature recorded at the same time both inside the healthy trees (29.53 °C) and in the ambient atmosphere (29.35 °C). The average temperature of the infested date palm increased slightly with an increase in the infestation level with the highest being 32.80 °C. Real-time analysis of a thermal image (TI) reveals if the tree is healthy, if it needs cutting or other remedial actions, or it has to be felled. If the tree is healthy, a uniform surface temperature distribution exists and the TI displays a uniform coloring, but if the color is not uniform, then deterioration/cavities may be present. 4–5 thermal images are usually sufficient to recognize the situations of an entire tree. A faster assessment usually needs 2–3 min, while an in-depth analysis requires less than 10 min. This technique wants less time than any other technologically advanced investigation system. The system has been used in all weather conditions, by night and day, in the summer and winter, with temperatures ranging from +2 to +35 °C.

2.5 Adaptive Thermal Sensing Technique to Support Precision Agriculture

Agriculture faces increasing challenges in food security, environmental protection, and water availability. Precision agriculture can certainly be a part of the solution to these challenges. Thermal RS manages the obtaining, preparing, and interpretation of data acquired mainly in the thermal infrared (TIR) region of the electromagnetic spectrum (Prakash 2000; Omran 2016b). A thermal wavelength region in terrestrial RS ranges from 3 to 35 μm. Data interpretation in the range from 3 to 5 μm is complicated due to overlap with solar reflection in day imagery. The 17–25 μm regions are still not well explored. Consequently, 8–14 μm regions have been of highest importance for thermal RS (Prakash 2000; Omran 2016b). This is where the atmosphere is fairly transparent and the signal is just lightly weakened by atmospheric absorption (Mallick 2006).

Thermal RS varies from optical RS by measuring emitted radiations from the surface of the target object, whereas optical RS measures reflected radiations on the target object under consideration (Sabins 1996). TIR offers a detectable and reliable "heat picture" of the environment. Thermal imagers identify long wave infrared, or heat. A TIR identifies objects that emit heat, regardless of light conditions, and the picture is unaffected by light, clothing, or inclement weather. Typically, hotter objects show as white, cooler objects show as black, of objects between these temperatures are shown in shades of gray.

The cost of data collection in TIR remote sensing is likely to be high due to the aircraft and instruments used. Field mapping is time-consuming and can therefore be expensive. Many field trips are required and data processing takes time both after and before results can be published. Here handheld thermal imaging cameras can be an alternative. All the data can be collected at the same time in the study area, and could therefore be processed and interpreted soon after collection. Therefore, the primary objective of this part is to suggest an adaptive thermal sensing technique to support precision agriculture.

2.5.1 Potential in Use of Thermal Sensing for Soil Thermal Properties

Although soil thermal properties are essential in many areas of engineering, micrometeorology, agronomy, irrigation, and soil science, they are seldom measured on a repetitive base. Explanations for this are vague, but may be related to a lack of appropriate instrumentation and fitting theory. The traditional method to estimate the temperature distribution and emissivity in soils is to use thermocouples to measure temperature at a shallow depth. When observing the spatial variability emissivity patterns (Fig. 2.6), there is a strong difference of emissivity over the soil surface, which is not noticeable from a visual assessment of the sample. Inside the prevailing matrix of emissivity values of 0.81–0.83 (shown in green color), there are clear areas with a much smaller values of around 0.76–0.78 (shown in blue) and larger

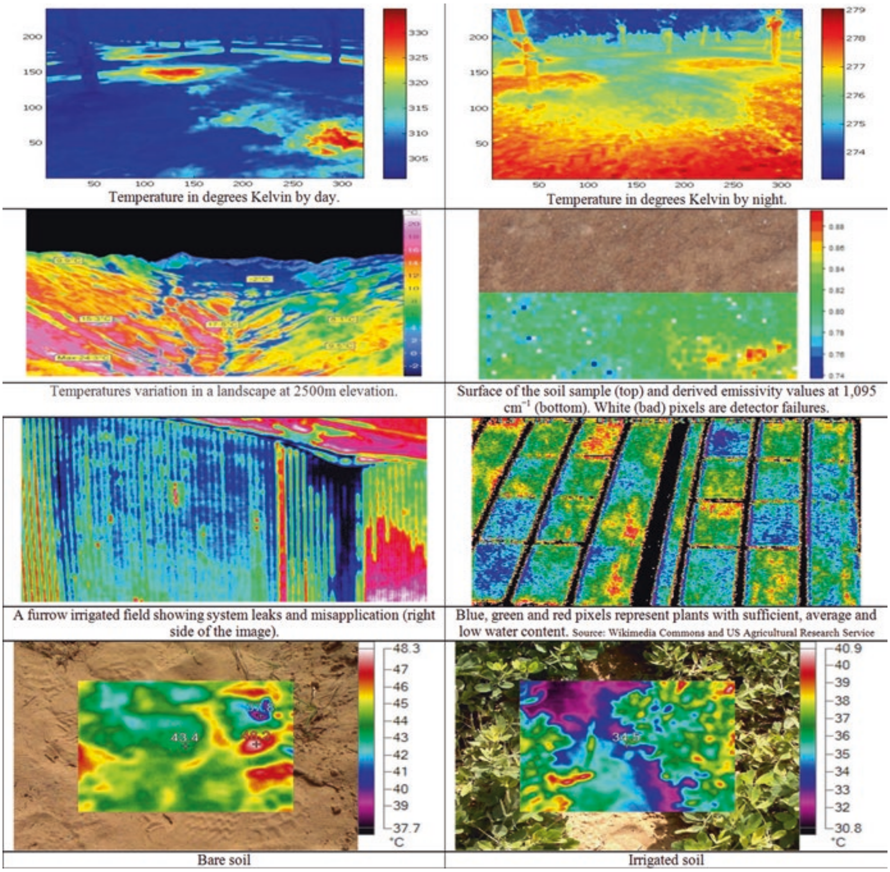

Fig. 2.6 Thermal images of spatial variability patterns of land temperature and emissivity show how variable temperatures vary in soil, orchard in the mountains, even between patches of land that are close together

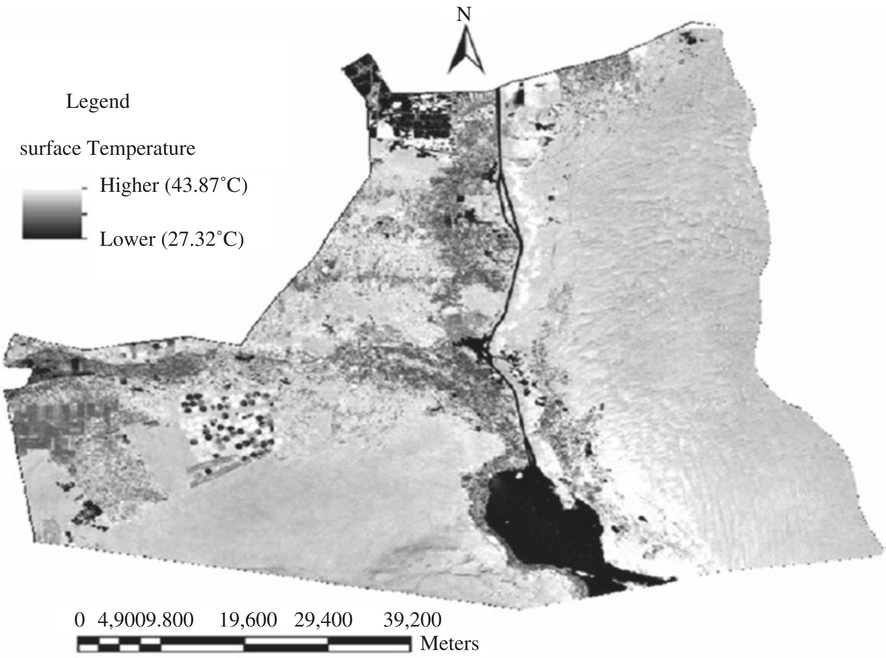

Fig. 2.7 Thermal image of land surface temperature for Ismailia Governorate at 10 April 2011

values of around 0.86–0.88 (shown in red). The detected spectral emissivity differences in the sample may be attributed to roughness, surface geometry, and compositional variation (Schlerf et al. 2010).

TIR remote sensing data are not only acquired from the camera, but some instruments that are thermal infrared sensitive have been also put into satellites. For example, Band 6 in the Landsat series of satellites and Band 10 and 11 in Landsat-8 collect data on TIR wavelengths. In addition, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) includes a thermal infrared sensor. TIR remote sensing can be used for lithological mapping, soil salinity detection, monitor water resources, and soil surface temperature mapping.

Omran (2012c) investigates the application of Landsat images for detecting changes in surface temperature from 1984 to 2011 in the Ismailia Governorate, Egypt. Figure 2.7 demonstrates the thermal image of land surface temperature for Ismailia Governorate on 10 April 2011. The results revealed a notable temperature change during the 27-year period. The urbanized area (37.65 °C in 1984 and 43.876 °C in 2011) and barren land (37.34 °C in 1984 and 42.801 °C in 2011) display the highest surface radiant temperature, while vegetated surfaces (28.73 °C in 1984 and 32.96 °C in 2011), water (25.94 °C in 1984 and 27.32 °C in 2011), and waterlogged (34.54 °C in 1984 and 35.60 °C in 2011) recorded low radiant temperature, respectively. The urban development between 1984 and 2011 has given growth to an average of 6.23 °C in surface radiant temperature.

2.5.2 Potential in Use of Imaging Thermal Infrared for Early Sensing of Peanut Leaf Spot

Groundnut, known as peanut (*Arachis hypogaea*), is a worldwide significance in light of its high oil content (EBTP 2015). Various fungal diseases attack peanut all over the world. Diseases cause serious economic losses in yield and quality of cultivated plants (MacLeod et al. 2004). Early leaf spot and late leaf spot are most devastating important foliar fungal disease of groundnut. These diseases are destructive and their early detection is essential in precision agriculture (Mahlein 2016; Omran 2016b). Disease damage assessment in peanut is being done traditionally by visual approach. Early detection of leaf spot methods is not available in practice. There is a need to develop a system that can control large areas within a short period during the season with limited labor and funds. Therefore, the aim of this part is to assess the potential of thermal infrared (TIR) imaging to early sensing of peanut leaf spot disease.

Figure 2.8 demonstrates the measurements performed in the TIR using heat sensing camera depicting the thermal behavior of the healthy and diseased canopy. The isotherm function permitted us to estimate the difference, in terms of absolute temperature (not taking into account emissivity variations). Thermal measurements were divided into two series: the first involving the whole canopy and the second one focusing on a single plant (Fig. 2.8). With regard to the first series, TIR measurements showed a higher radiance of the diseased area compared to that of the healthy one. Such thermal behavior may be found due to the diminished absorbing

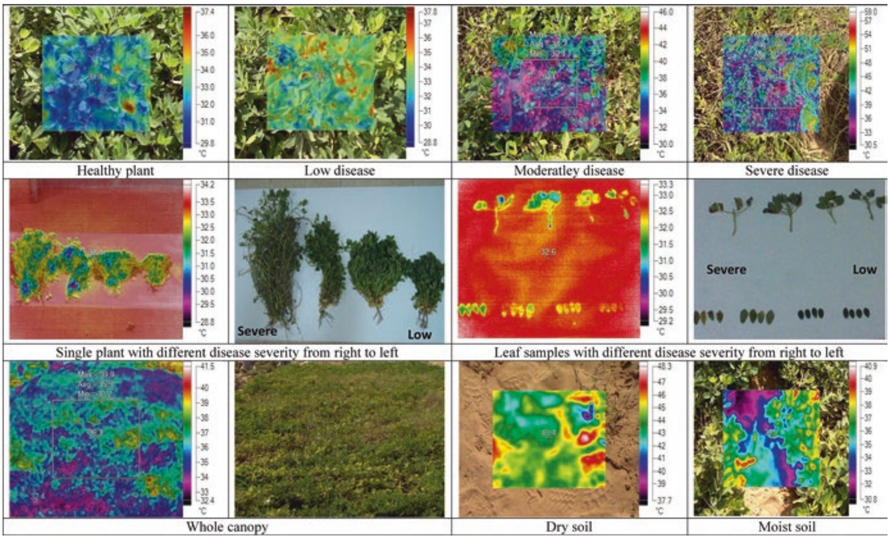

Fig. 2.8 Thermal behavior of the healthy and diseased canopy for the whole and single peanut plant and the thermal behavior differences between dry and moist soil

efficiency of the root in the diseased plants, which is more evident in the hottest hours of the day, when the water requirement of the plant is higher.

As in Fig. 2.8, leaf temperature is an indicator of stomatal conductance because stomatal opening increases with decreasing temperature due to evapotranspiration. The physiological responses of peanut leaves to biotic stress, such as fungal infection, can easily be monitored using thermal imaging due to the spore density, which covers the leaf surface and causes a masking effect. This might be the reason of decreasing leaf surface temperature of the infected plants. Presymptomatic decrease in leaf temperature was found about 1.3 °C lower than the healthy leaves. Xu et al. (2006) show that presymptomatic decrease in leaf temperature about 0.5–1.3 °C lower than the healthy leaves. Thermal imagery can help in the detection of leaf spot infection in peanut from the first hours of successful germination of conidiospores. The temperature difference allowed the discrimination between the infected and healthy leaves before the appearance of visible necrosis on leaves.

The second series of measurements in Fig. 2.8 were performed on single plants in which the thermal behavior and the response in the photographic TIR were monitored during a day. The data demonstrated that the diseased plant's temperature was 2.2 °C higher than that of the healthy one. The thermal behavior of either healthy or diseased plants (the diseased area always more radiant than the healthy one) has a wider varied range, which is in accordance with my expectation. In fact, as *cercospora* leaf spot is a necrotic disease, and as the diseased area was severely infected, a remarkably different spectral response of necrotic or strongly dehydrated tissue compared to that of healthy tissue was expected. Dead or strongly damaged leaf tissue has a lower thermal capacity than a normal tissue, and, consequently, can be more easily heated and displays a stronger radiance. However, it can also be more easily cooled than the tissue of healthy plants and this fact explains the fast radiance in the diseased plant, corresponding to the decrease of air temperature in the afternoon. Additionally, in this case, it is important to check the thermal influence of the bare soil, of reflectance "interference" detected by the change of the measurement angle of the instrument in the healthy area and in the diseased one.

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Site-Specific Nutrient Management (SSNM): A Unique Approach Towards Maintaining Soil Health

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Abstract

Agricultural production in India has increased from ~50 Mt in 1950 to ~251 Mt in 2011–2012 by the intensive use of external inputs. The negative nutrient balance due to the imbalanced fertilization to the tune of ~8–10 Mt is reported, resulting in nutrient mining, stagnation and/or deceleration in productivity and soil health decline. The indispensable role of geo-informatics (RS, GPS and GIS) aided site-specific nutrient management (SSNM) for efficient use of resources and nutrients is suggested for achieving the projected food production target ~300 Mt by 2025. Towards the better response of SSNM over blanket fertilizer recommendation in terms of nutrient use efficiency (NUE), productivity and profitability is reported and discussed under Indian context. Long-term pooled data across several locations in India revealed an increase in yield of rice and wheat crops by ~12 and 17% and profitability by ~14 and 13%, respectively as an outcome of SSNM. Web based farmers' advisory launched recently in the

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state of West Bengal is reported. The development of such dissemination mechanisms that consolidates the complex and knowledge-intensive SSNM information into simple delivery system is suggested for rapid implementation by the farmers towards maintaining soil health and ensuring future generation food security.

Keywords
Soil health • Nutrient mining • Nutrient use efficiency (NUE) • Geo-informatics • Site-specific nutrient management (SSNM)

3.1 Introduction

Agriculture is the major land use across the globe. Out of total land area of ~14 billion ha globally, ~3 billion ha is potentially cultivable, of which only half (~1.5 billion ha) is actually cultivated at different productivity levels owing to certain constraints (Yadav and Sarkar 2009). Thus, very limited area is available for cultivation and agricultural development for the fast growing worldwide population.

The sustainability of our world depends fundamentally on nutrients. In order to feed ~7 billion people, humans have more than doubled global land based cycling of nutrients. The twenty first century population facing food insecurity and malnutrition in most of Africa and parts of South America and Asia, meanwhile the injudicious uses of mineral fertilizers with the overuse of nitrogen and phosphorus in worldwide leading to pollution of freshwaters, eutrophication and acidification of terrestrial and coastal ecosystems, decreasing biodiversity under changing climatic scenario. The future generation of worldwide facing the problems of per capita land availability, currently it having of 0.23 ha will decrease to 0.14 ha in 2050, the freshwater supply also will decrease to the scarcity level in many countries and extreme forms of degradation will affect ~300 M ha of very productive agricultural land, this situation particularly accrue in the countries where farmers, government cannot invest in soil restoration (Nieder 2006).

The Green Revolution in mid-1960s ensured food security in the developing world through adoption of novel inputs for the agricultural production system mainly high quality of seed along with improved production technologies. However, indiscriminate exploitation of natural resources with no regard to their carrying capacity and non-judicious use of agrochemicals are the factors responsible for post-green revolution problems. Meanwhile the degradation of soil/land and water resources quality, diversity loss of flora and fauna, change in the utilization pattern of agricultural land towards the industrializations and urbanizations, environmental degradation and resultant climate change are the important post-green revolution issues leading to exhaustion in agricultural production thereby threatening for the globally sustainable food security (Paroda 2003).

Most of the agricultural production system worldwide facing the insufficient access to nutrients still limits food production and contributes to land degradation.

These potential risks for future global food security, pointing to the need for their prudent use nutrients as emerging global challenges of the past three decades (Basu 2012). The sustainable management practices towards enhancing the agricultural production manifold, particularly in case of food grain crops from ~50 Mt in 1950 to ~251 Mt in 2011–2012, due to record production of wheat, maize, pulses and oilseeds (http://www.icar.org.in). For the future generation of country the estimated demands of food grain to increase ~300 Mt by 2025 for which the country would require ~45 Mt of nutrients. The sustainable food production each of these activities further modified the world's nutrient flows, altering the cycles of nitrogen (N), phosphorus (P), carbon (C), sulphur (S) and many other trace elements (ICAR 2008). Further this has to be achieved against several constraints viz. unabated land degradation (~121 Mt ha degraded land), soil health deterioration (depletion of soil organic matter (SOM), soil nutrient mining, soil acidity/salinity, etc.), shrinking water resources and climate change affecting mostly the marginal and small farmers constituting ~80% of the Indian farming community (ICAR and NAAS 2010; Rawat 2012).

The best management practices (BMPs) for sustainable food production to mitigate the world food insecurity and their inadequate management is leading to land degradation, loss of biodiversity, climate change and adverse impacts on human health. The balanced fertilization of nutrients is a key issue for higher crop productivity and agricultural sustainability. During the post-green revolution era (1969–2007), the food grain production of country more than doubled from ~98 Mt to a record ~212 Mt in 2001–2002, while the mineral fertilization use increased ~12 times from 1.95 Mt to ~23 Mt in 2007–2008 (Rao 2009). These concerns have been expressed over the decline in response per unit N-P-K from ~12 in 1960–1969 to ~8 in 2000–2007 (Singh 2008). The decrease in the fertilizer response ratio could be attributed to deterioration of soil health as evident from widespread multi-nutrient deficiencies and falling soil organic carbon (SOC) level over the years especially in the irrigated areas of the country (Biswas and Sharma 2008a). However, Singh (2008) reported that deterioration in soil health or soil quality is not solely responsible for such declining response (Bahadur et al. 2016; Dotaniya et al. 2016; Meena et al. 2016). Rather, it appears that this issue has been related more to principle of diminishing return with quantum increase in N-P-K use over the years (Tiwari 2002).

With almost no opportunity to increase the area under cultivation over ~142 Mt ha, much of the desired increase in food grain production has to be attained through yield enhancement per unit area productivity. To sustain production demands, the productivity of major crops has to increase annually by ~3–8% (NAAS 2006). Much of this has to be met by increasing genetic potential and improving production efficiency of the resources and inputs like water and nutrients. The vast potential of the fragile ecosystem of dry land farming with resource poor and risk shy farmers which received much less attention in the "Green Revolution" era also needs to be harnessed in this regard.

Whichever way we look at it, "Our Nutrient World" presents a major scientific, social and political challenge: to produce more food and energy for a growing world population, while simultaneously reducing the pollution threats on environment, climate and human health. These growing concerns about degraded soil health as well as its quality and declining factor productivity has raised concern on the sustainable food production system of India. For example, research on farmers' fields from last three decade has also revealed that there are no compelling reports of significant increases in input use efficiency mainly NUE under rice-wheat cropping system (Dobermann and Cassman 2002). From the last decade reports the average crop recovery efficiency of N-fertilization is still very low ~30% (Dobermann 2000). The major factors contributing to the low and declining crop responses to NUE are (a) through the continuous nutrient mining due to injudicious application of fertilizers, which is leading to depletion of some of the major, secondary and micronutrients (b) less awareness of farmers towards the fertilizers use (c) loss of fertilizers mainly N during the mismanagement of irrigation systems. Furthermore, such low efficiency of resources and fertilizer inputs has impacted the production costs with serious environmental consequences (Johnston et al. 2009; Meena et al. 2015a; Yadav et al. 2016; Choudhary et al. 2016).

Recent research conducted in various countries including India (Dobermann et al. 2002; Wang et al. 2001; Wopereis et al. 1999; Angus et al. 1990) has reported that the limitations of the comprehensive fertilizer recommendations with least regard to the variability in soil fertility and productivity practiced across Asia. Adoption of precision technologies for more efficient use of resources and nutrients becomes more relevant in the current production scenario. Site-specific integrated nutrient management (SSINM) involving use of inorganic/organic sources along with spatial and temporal soil variability, crop requirements of nutrients and cropping systems, soil capacity to supply nutrients, utilization efficiency of the nutrient and productive capacity of the varieties under BMPs with improved NUE and without deteriorating soil and environmental quality is the most ideal system that needs to be practiced to achieve the targeted goals (Tiwari 2007; Meena et al. 2015b; Verma et al. 2015a, b).

3.2 Major Problems Related to Soil Health

The soil health is the capacity of a soil to function within natural or managed ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health. In the context of agriculture, it may refer to its ability to sustain productivity. The United Nations Millennium Development Task Force on hunger made "Soil Health Enhancement" as one of the five recommendations for increasing agricultural productivity and fight hunger in India as a component of Millennium Development Goals (MDGs) (Singh 2008). The soil health is governed by a number of physical, chemical and biological attributes and processes and is expressed by different quantitative and qualitative measures of these attributes, as also by outcomes that are governed by the soil such as productivity, nutrient and water use efficiencies (WUE) and quality of produce (Tiwari et al.

2009). The maintenance of good soil health needs balanced fertilization, which includes application of all the required plant nutrients in proper amount and form.

The major issues of soil health under Indian context include: (1) physical degradation caused by compaction, crusting, water logging and soil erosion; (2) chemical degradation caused by wide nutrient gap between nutrient demand and supply; (3) the soil biological degradation due to SOM depletion and loss of fauna and flora and (4) soil-plant-environmental pollution (Singh 2008).

The degradation in soil health as is evident from deceleration in agricultural productivity, decrease in NUE, the response ratio has emerged as a major factor responsible for stagnation in agricultural production (Tiwari et al. 2009; Biswas and Sharma 2008a). However, the soil erosion and land degradation are among the glaring environmental problems adversely affecting soil productivity and continuously converting productive lands into wastelands. Intensive cultivation, raising more crops from unit area of land, resulted in a rapid depletion of SOM content of soil and adversely affected the soil's physical properties. It is an irony that while nature takes ~300 years to form only one cm of top soil, as much as ~5334 Mt of soil gets eroded every year on a country basis accounting ~17 t ha^{-1} $year^{-1}$. Thus, degradation of land resources is posing a big threat to the natural resources resulting in soil and nutrient losses (~6 Mt N-P-K $year^{-1}$), the loss in productivity and destruction of floral and faunal wealth, which ultimately adversely impacts human life (Singh 2008).

3.3 Nutrient Use Efficiency: An Overview

Nowadays the term NUE gained more attention with the rising of fertilizer costs and continued concern over soil and environmental pollutions. The nutrient or fertilizer use efficiency (FUE) can be viewed from different perspectives based on yield, recovery or removal. Among the most common expressions of efficiency is the recovery efficiency (RE) of fertilizer applied and these nutrients recovered in above ground plant biomass during the crop growing period. The fertilizer utilization rate and crop recovery efficiency under favourable conditions for N is ~50–70%, 10–25% for P (~15% average) and 50–60% for K under various cropping and soil types.

3.3.1 Current Status of NUE: Global vis-à-vis Indian Scenario

The Indian scenario of NUE under the BMPs as per the previous reports or available information suggests that the N recovery efficiency for fields managed by farmers ranges from ~20 to 30% under dryland/rainfed conditions and ~30 to 40% under irrigated conditions of various cropping system (Roberts 2008). The N for the rice crop is ~31% for irrigated conditions grown by the Asian farmers and ~40% under field-specific management condition. In India, N recovery ~18% for wheat grown under poor weather conditions, but ~49% when grown under BMPs along with

RMPs (Cassman et al. 2002). While most of the focus on NUE is on N, and the phosphorus use efficiency (PUE) is also of interest because it is one of the least available and least mobile mineral nutrients in soil system (Meena et al. 2015c; Verma et al. 2015a). First year recovery of applied fertilizer P ranges ~10% to as high as ~30%. However, since fertilizer P is considered most immobile in the soil system and reaction (i.e. fixation, precipitation) with other soil minerals is relatively slow, long-term recovery of P by subsequent crops can be much higher as compared to others nutrients. There is little information available about potassium use efficiency (KUE). However, it is generally considered to have a significantly higher KUE as compared to N and P because it is immobile in most soils. The first year recovery of applied K ranged from ~20 to 60% (Roberts 2008).

Coming down to the Indian scenario, there exists a wide gap between the nutrients applied and those removed by crops under intensive agriculture resulting in a negative balance, which at the national level is estimated to be ~8–10 Mt resulted in nutrient mining which ultimately is responsible for depleting soil health as well as its quality (Singh 2008; Tiwari 2002). The imbalanced fertilization particularly in respect of N-P-K induces declining in crop productivity and agricultural sustainability. Out of the 17 nutrients, focus has been on nitrogen, followed by phosphorus; secondary and micronutrient have not been given due attention. As a consequence, deficiencies of N, P, K, S, Zn, B, Fe, Mn and Cu have been reported to the extent of ~89, 80, 50, 41, 48, 33, 12, 5 and 3%, respectively. These deficiencies of nutrients are becoming more widespread and critical. As per the previous reports the NUE applied N (~30–50%), P (~15–20%), K (70–80%), Zn (2–5%), Fe (1–2%) and Cu (1–2%) in Indian soils. Thus, the problems of nutrient deficiencies are aggravated further because of very less NUE of applied nutrients, particularly of P and micronutrients, i.e. Zn, Fe, Cu and Mn (Singh 2008).

To increase NUE and to minimize its negative impacts on soil and environment have been the focal points in the world from the few decades. The NUE or FUE can be optimized by fertilizer BMPs that apply right source of nutrients, at the right rate, right time, right place and with the right tools. In such context geo-informatics aided site-specific nutrient management (SSNM), etc., are some of the most viable options for improving NUE and maintain sustainable food production system (Yan et al. 2008).

3.4 Geo-Informatics in Nutrient Management: A Twenty-First Century Paradigm Shift

Nowadays the geo-informatics is the fast emerging science encompassing the modern tools of Remote Sensing (RS), Global Positioning System (GPS), Geographic Information System (GIS) and simulation models. The combination of these technologies provides a cost-effective means of acquiring high resolution real time data through RS, geo-referencing the ground truth data with GPS, data management and analysis through GIS and putting all data in an information system and utilization of the information for a specific purpose. These key elements that differentiate geo-informatics from other areas of information technology are that, all input data is being geo-coded, i.e. has an address in 3-D space and is linked to some locality on the surface of earth (Sharma 2004).

The spatial and temporal variability is the inherent towards the sustainable agricultural production systems. Therefore, BMPs require intensive soil sampling to assess variability of nutrients across the field. The GIS provides the opportunity to catalog the data and map the variability of different nutrients, and to do various types of queries and analyses. These data relevant to the RS adds another source of spatial information. However, the satellite imagery can be geo-referenced and included in the GIS database for each particular location.

These data layers associated with different wavelengths of reflected energy can then be associated with other data layers of information and manipulated and analysed with GIS tools to determine relationships of interest and importance to modern crop and soil management. The nutrient stress, pest pressures and weather effects are among the factors that can be included along with the new sensors, monitors, and wireless communication systems are also leading to revolutionary applications of these technologies in various fields of application (Reetz 2000; Reetz et al. 2001).

3.5 Maintaining Soil Health vis-a-vis SSNM

The degraded soil quality and health is leading to reduction in crop productivity due to high quantity of nutrient mining and imbalanced fertilization and plant growth promoters (PGP) for sustainable soil management. The declining in soil fertility status of Indian soils due to negative balance of nutrients is likely to end with irreversible damage to the nutrient supply system if blanket fertilization is followed. With the improved management practices (IMPs) the generalized approach and change in associated knowledge systems leads to nutrient application, while ignoring individual farm diversity with lower crop yield. As an outcome production response of fertilizations has decreased from ~17 kg grain kg^{-1} nutrient in 1951 to ~6 kg grain kg^{-1} fertilizers 2013–2014, which ideally should range between ~18 and 25 kg grain kg^{-1} nutrients. The declining response to applied nutrients, decreased soil organic carbon (SOC) and soil quality suggest for BMPs to improve factor productivity and sustain long-term soil quality/health for future generation (http://www.rkmp.co.in/).

Some of the recent finding of research conducted in many Asian countries, including North West India (Ladha et al. 2003; Pathak et al. 2003), has demonstrated limitations of the current approach of fixed-rate, fixed-time fertilization being made for large areas (Timsina and Connor 2001). This also helps to explain why NUE is usually poor, the use of P and K fertilizers is often not balanced with crop requirements and other nutrients and, as a result, profitability is not optimized (Dobermann et al. 1998; Olk et al. 1999).

Of late, SSNM is gaining popularity due to the its superiority over blanket recommended management practices (RMPs) as it takes into account site, season and crop growth variability in making soil sustainability. It attempts to optimize the use of nutrients from all sources—soil, irrigation water, biological fixation (i.e. N-fixation), SOM and a fertilizer which enables farmers to apply the right amount of nutrients at the right time when the crop needs them the most. These nutrients applications thus match the crop demands, thereby, minimizing the risk of over-application of fertilizers. It also ensures balanced application of all nutrients to maintain the long-term productivity and soil quality (Singh 2008).

In fact, SSNM is a geo-informatics based approach (RS, GPS, GIS and sensors) as opposed to RMPs followed over an extensive area irrespective of soils, crop(s) and/or cropping sequence(s)/land use concerned. The site-specific mode takes into account the spatial variations in nutrient status cutting down the possibilities of over use or under use of the costly inputs. A system's approach (Decision Support System—DSS) with well-developed analytical frameworks, databases and powerful simulation models aid in further improvement of SSNM (Sen et al. 2007).

The essential pre-requisite for SSNM is GPS and GIS aided mapping of soil properties specially soil nutrients, which provides information on changing soil fertility status under different crop(s) and/or cropping sequence(s) under diverse agro-ecologies together with scope of further monitoring and updating of databases. The activities involved comprise of the soil nutrient status based upon geo-referenced soil sampling, laboratory analysis for generating dependable analytical data and database structuring in GIS environment/DSS.

3.6 Rigorous Soil Testing for Better SSNM: The Need Indeed

For precise assessment of the nutrient need of diverse crops and soils, with the faithful soil testing and performing manure/fertilizer recommendations for individual fields would be important which will ensure balanced use of fertilizers, organics and amendments (Tiwari 2008). Therefore, it becomes evident that the ultimate success of SSNM will certainly depend upon accurate soil testing that underpins this novel technology.

3.7 The Approach and Methodology

The soil fertility can be monitored and evaluated by a set of measurable attributes termed indicators. These indicators can be broadly grouped as nutrient status and environmental conditions (physical, chemical and biological indicators). Since the beginning of the 1990s, this concept has received unprecedented attention and has been applied in such research areas as suitability determination of species, relations between species, community structure and niche construction. The niche-fitness theory has also been applied to population, urban economics and other study fields. The niche-fitness model, which expands on the basis of niche, can reflect how well-suited crops are for the soil's environmental conditions. It can also diagnose the indicators that restrict the growth of crops.

3.7.1 GIS Based Fertility Mapping

Nowadays the rapid increase of population and limited land resources constitute a problem for most of the countries as they face acute scarcity of land for food production. In order to obtain higher output and productivity, more and more chemical fertilizers are applied into the farmland, which leads to soil/water pollution, fertility degradation and nutrient imbalance, meanwhile the utilization of modern technologies for promoting the sustainable food production and coordinated development of agriculture. Towards the wide spread and adoption of fertilizer recommendations through SSNM following classical soil testing approach require extensive soil testing methods. However, GPS and GIS based soil fertility mapping can provide a cost intensive alternative offering more precise and efficient nutrient management for sustainable food production. The soil samples are subjected to analysis for soil quality and its health. These methodologies are followed by integration of location information of the sampling point (latitude/longitude) with that of the corresponding attribute information in a GIS platform to create continuous surface maps of the attribute. The each point in the map, created through interpolation techniques allows estimation of attribute values from the latitude/longitude (Iqbal et al. 2005).

Two most important factors that determine the success and accuracy of soil fertility mapping are proper sampling and interpolation technique. To make meaningful estimates, sampling points need to be taken on a grid sufficiently small to intercept the variability of soils. The grid sampling is the most widely used method till date to characterize soil variability. Nowadays soil fertility mapping on the basis of GIS decision support tool helps within the study area and the maps generated through this approach can give a clear visual indication of changing fertility scenario with time. Besides the logistical and economic advantages of implementing such a system, once established, can become an effective extension tool. Thus, farmers become more aware of how their fields rank within the landscape in terms of basic soil fertility status, which in turn enables a system for more rationale use of fertilizers. The indicator for successful dissemination of SSNM is the times when many farmers quickly obtain and use a science based, BMPs and RMPs to their specific field, crop and season (Satyanarayana et al. 2011).

3.8 GIS Aided Soil Nutrient Mapping in the State of Jharkhand and West Bengal: Case Study

A very recently, ICAR-NBSS&LUP has successfully completed the GIS based soil nutrient mapping for the states of Jharkhand (~8 Mt ha) and West Bengal (~9 Mt ha), India under the project on “Soil Nutrient Mapping” to measure the spatial variability in nutrient status and/or soil fertility mapping towards rational land use planning (NBSS and LUP 2006, 2012) (Figs. 3.1, 3.2, and 3.3). These maps were used as an SSNM or fertilizer recommendation tool to positively impact crop yields in farmers’ field for the both states.

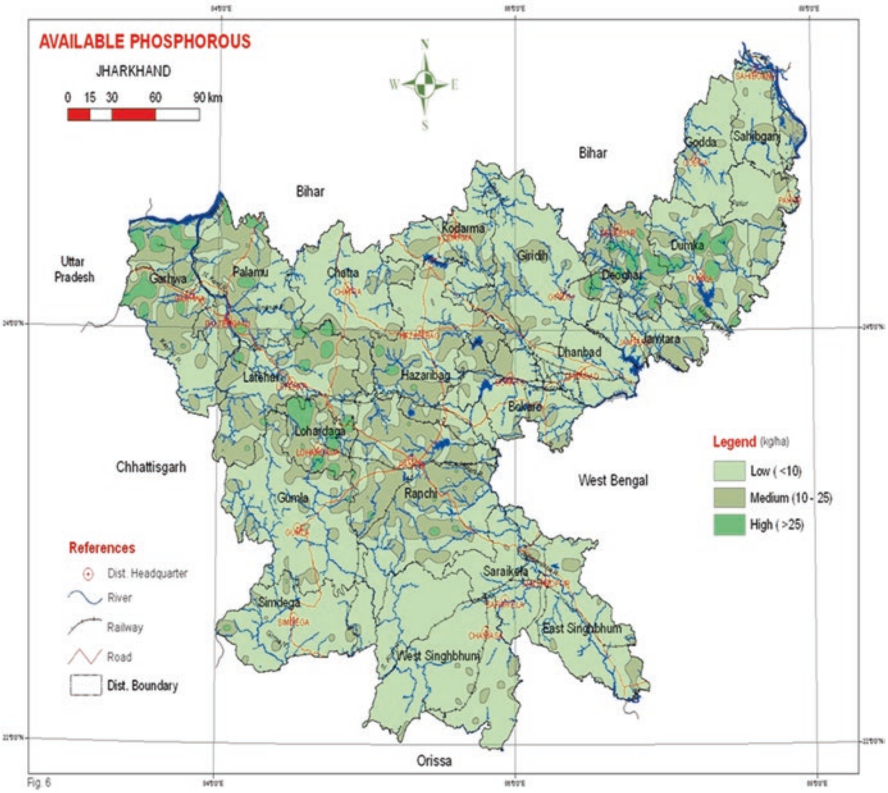

Fig. 3.1 Available phosphorus, Jharkhand, India

For this endeavour surface soil samples (~25 cm) were collected at ~1 km grid intervals with taking of five representative composite soil samples in and around each grid point and mixed together to have one composite sample for each grid point towards chemical analysis for 22 and 18 districts of Jharkhand and West Bengal, respectively. The analysis of important soil parameters including soil pH, EC, surface texture, SOC, available N, P, K, S and micronutrients (Cu, Zn, Fe, Mn, B and Mo) was done following standard methods. Macro, major and micronutrients analysed for each point were ranked as low, medium and high; micronutrients as sufficient and deficient; and pH class from extremely acidic to neutral following standard ratings (Govt. of West Bengal 2005).

The database consisting of macro, major and micronutrients, texture, SOC and pH for each grid points were developed in ARC GIS 9.2. The database also has location of the each geo-referenced point including latitude, longitude and the name of village, block and district. Inverse weighted distance (IWD)—a GIS based interpolation technique was used to develop individual maps of the soil nutrients of each district of Jharkhand and West Bengal. The maps thus generated provided requisite information regarding the extent of soil acidity/fertility status of the individual

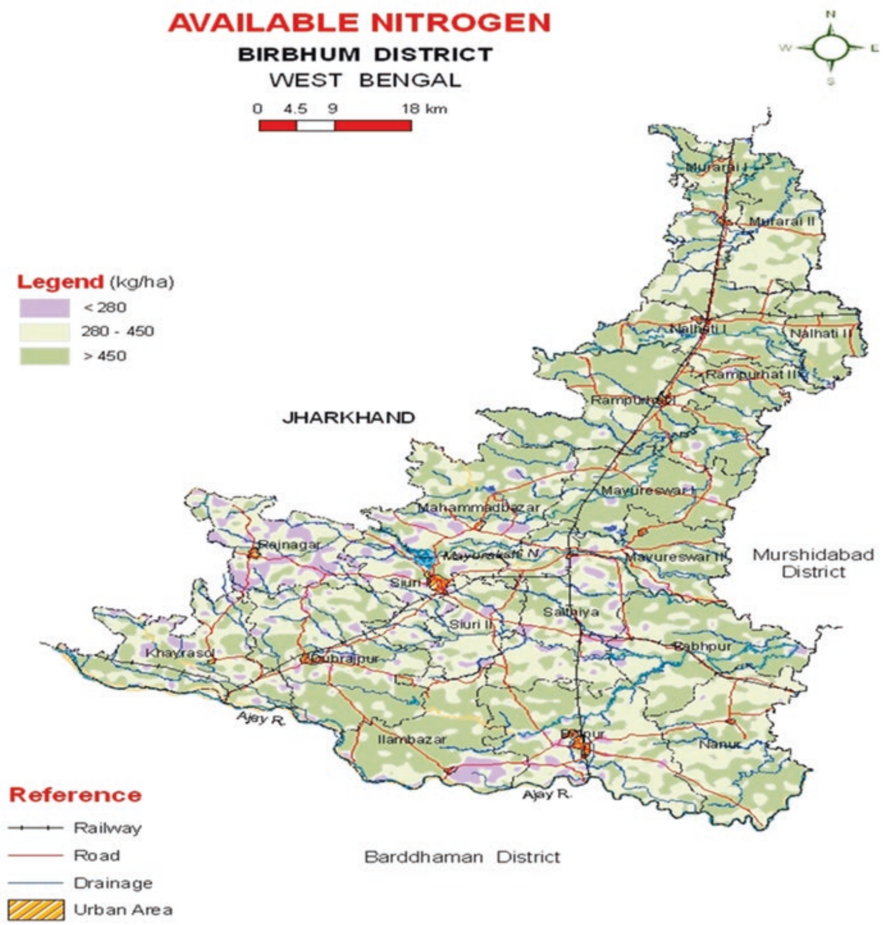

Fig. 3.2 Available nitrogen, Birbhum district, West Bengal, India

district very useful for identification of site-specific problems for subsequent crop planning/alternate land use for better crop production.

Soil acidity together with the low P and S status, moderate N and K status as well as deficient zones of zinc, copper and boron indicated in general the low fertility status in the state of Jharkhand while low status of P, K, Zn and B together restricted agricultural production in large part of the districts of Purulia, Bankura, Koch Bihar, Dakshin Dinajpur, Malda, Murshidabad, Uttar Dinajpur and Purba and Paschim Medinipur in West Bengal due to inadequate supply of the nutrients alone or in integrated manner. Widespread soil acidity problem was also encountered in West Bengal impairing sustainable crop productivity.

Thematic maps of low balance of P, K and Zn were also examined and integrated together in GIS for Birbhum district (~4545 km^2), West Bengal (Fig. 3.3). The results revealed low balance of P, K and Zn in the seven combinations indicating

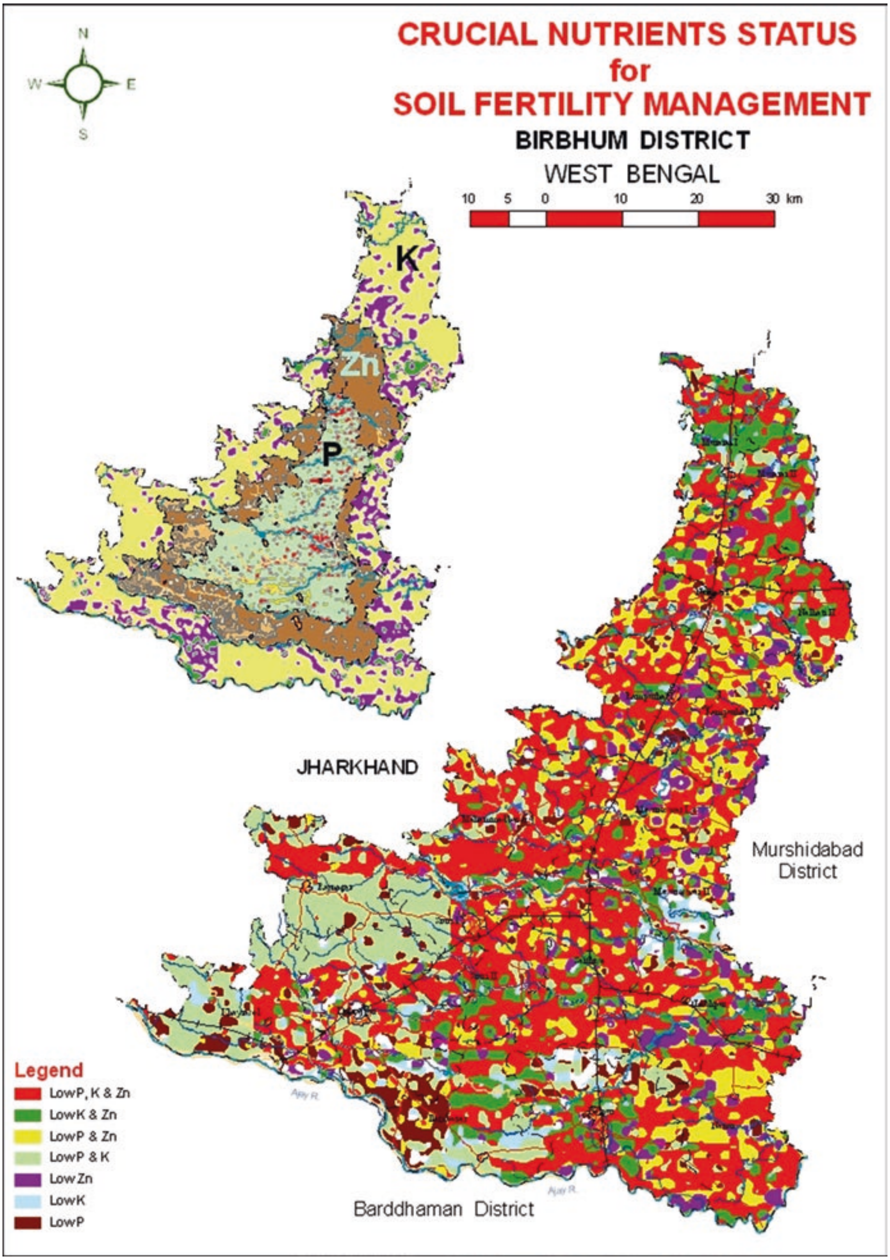

Fig. 3.3 Multi-nutrient deficiency, Birbhum district, West Bengal, India

multi-nutrient deficiency in the district. The combination of P, K and Zn were deficient on larger area (~37%) while less area was affected with combination of low balance of two nutrients like P and K (~16%); P and Zn (~14%) and K and Zn (~12%). The problem of low balance of single nutrient viz. P (~6%), K (~4%) and Zn (~6%) alone occurred only on very small area of the district. Such findings, as an outcome of GIS based soil nutrient mapping suggested the need for adopting adequate soil management practices (SMPs) towards optimizing agricultural production under changing climatic scenario.

3.8.1 Decision Support System

The DSS help in extension of SSNM and support appropriate nutrient management decisions for soil nutrients at the farmers' as well as in research fields.

3.9 Computer Based Decision Tools

The computers are one option for accessing decision tools via the internet. Mobile phone with SMS (short message service) capability is another alternative which is available to many small-scale farmers of the country. Another way to reach many farmers with mobile phones is through interactive voice response (IVR) (Johnston et al. 2009).

3.10 Launching of Web Based Farmer's Advisory in the State of West Bengal, India: An Example

The promoting Web-GIS venture is expected to improve information access and effective delivery of services to the farming community for their decision-making, thereby improving productivity and profitability of farmers through better advisory systems. Recently such type of Farmers' Advisory System has been developed from GIS aided soil nutrient maps/soil test data of West Bengal generated by ICAR-NBSS&LUP supported by the Department of Agriculture, Government of West Bengal and was hosted on www.wbagrisnet.gov.in of National Informatics Centre (NIC), Govt. of India server.

These types of advisory were also linked with mobile cell phone services. Web application acts as a DSS that calculates number of alternate options, which could be selected by the farmers depending upon their requirement, availability of irrigation water and socio-economic conditions (Fig. 3.4). With the requisite back up knowledge for fertilizer and crop planning taking in to consideration the advisory offer rendered to the rice, vegetable, pulse and fruit growers of West Bengal (Sen et al. 2012).

Farmers' advisory, based on knowledge base (information heuristises), inference engine (analyses knowledge base) and end user interface (accepting inputs and

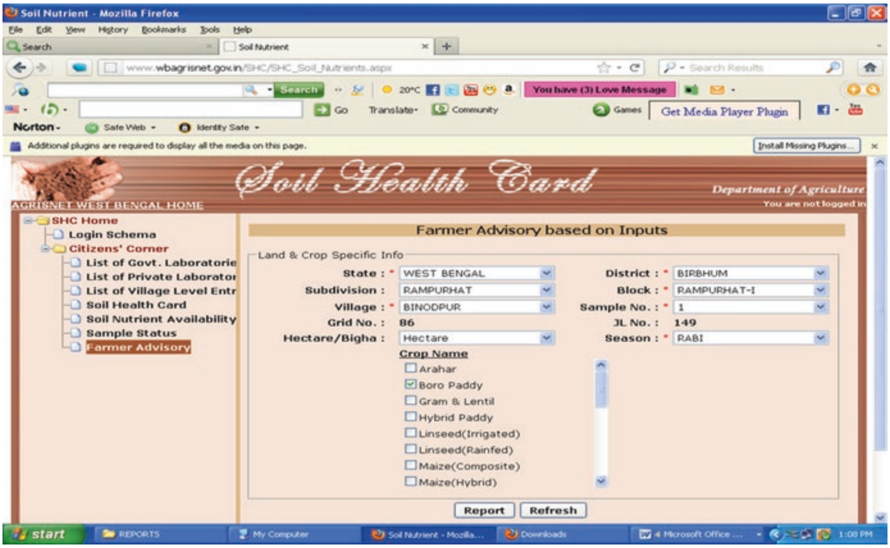

Fig. 3.4 User interface for visualizing the database and selection of desired attributes

generating outputs), has an open architect for addition/deletion of soil test values and the new interest of farming likely to be arising in future. It generates information on ranges of soil pH, macro and micronutrient status and calculates nutrient requirement; recommends type and amount of fertilizers, SOM and soil ameliorants for a given crop/variety or land use of a village in the different seasons of a particular agricultural year following a justified crop cycle.

This type of advisory also recommends methods and time of fertilizer applications with its BMPs and RMPs. It therefore becomes evident that the SSNM practices with IMPs not only help in maintaining the soil sustainability and hence better crop, web based farmers' advisory and/or the mobile phone based service help the farmers to receive information about the nutrient management at timed intervals through personal cell phones as per the cropping season for better productivity (Sen et al. 2012).

3.11 SSNM: Impact on Yield and NUE

In the soil test based approach to calculate site-specific fertilizer recommendations, fertilizer rates are recommended based on the concept of crop removal, with an adjustment for soil residual nutrients management. While this approach actually fits most production systems in India quite well, given that most of the crop biomass is removed from harvested fields, the role that residual soil nutrients play in meeting crop nutrient requirements becomes a challenge for intensive cropping system. For example, if a soil tests medium or low in most plant nutrients, then application of these nutrients based on crop removal from a target yield is going to address these

Table 3.1 Effect of site-specific nutrient management (SSNM) on wheat productivity (t ha^{-1}) and economic returns (Rs ha^{-1}, in parenthesis) at seven locations in India (source: Singh and Bansal 2010)

Site	FP[a]	SR[b]	SSNM	Increase over SR increase over FP [% (Rs ha^{-1})]	Increase over FP [% (Rs ha^{-1})]
Ranchi	2.56 (1575)	4.15 (25,276)	4.06 (26,854)	10.0 (1578)	58.5 (25,309)
Modipuram	4.77 (29,292)	4.90 (31,859)	6.43 (58,083)	31.0 (26,224)	46.5 (28,791)
Kanpur	4.72 (7258)	5.45 (17,644)	6.00 (31,338)	10.1 (13,694)	27.1 (24,080)
Ludhiana	5.45 (27,772)	6.28 (39,105)	6.55 (46,219)	4.3 (7114)	20.1 (18,447)
Sabour	3.92 (18,306)	4.97 (28,614)	5.82 (45,116)	17.1 (16,502)	48.7 (26,810)
Pantnagar	3.87 (7828)	5.10 (14,276)	6.39 (19,426)	25.3 (5150)	66.0 (11,598)
Palampur	2.64 (55,122)	3.76 (54,583)	3.87 (60,905)	3.0 (6322)	46.5 (5783)

[a]FP = Farmers' practice
[b]SR = State fertilizer recommendation

nutrient demands. However, on soils where the soil nutrient analysis indicates a high level of nutrient supply, the issue of whether to apply the nutrient at removal rates becomes a challenge to the researcher. The best option, therefore, is to apply all macronutrients and secondary nutrients that are required to meet crop yield removal and those micronutrients that soil testing show to be marginal or deficient. This then provides the environment for full yield expression in the absence of any nutrient deficiency. Once this yield potential of a site has been determined, the next step is to refine nutrient application rates with further field trials (Singh and Bansal 2010).

The positive impact of this approach to fertilization was clearly showed in a series of research experiments conducted by on soil test based SSNM in rice-rice and rice-wheat cropping systems in seven different locations of India in the Indo-Gangetic Plain (IGP) which produces ~50% of the country's food grains enough to feed ~40% of the total population of India. The production of grains is, however, not uniform across the IGP regions because of various inadequacies in crop management of which rampant imbalanced fertilizations is a key influence for stagnating or declining crop productivity, loss of SOC, declining water levels, NUE/FUE, nutrient imbalance, including multi-nutrient deficiencies and soil quality and its health (Khurana et al. 2008).

Some of the recent studies reported that when the yield-limiting nutrients were recognized and applied at respective locations as an SSNM treatment, it was able to generate potential productivity and profitability over farmers' practice across most of the agro ecological regions with the RMPs. A smaller gap existed between SSNM and the state recommendation, although most sites still suggested an economic advantage for the SSNM approach (Table 3.1).

Results from on-farm or research field experiments (Dwivedi et al. 2009) comparing soil test based SSNM with other RMPs along with BMPs in pearl

Table 3.2 Positive impact of SSNM on grain yields and nutrient use efficiency under rice-wheat cropping system in North West India (source: Singh and Bansal 2010)

Parameters	Rice		Wheat	
	Farmers practices	SSNM	Farmers practices	SSNM
Grain yield (kg ha^{-1})	5.1	6.0	4.2	4.7
AEN (kg grain kg^{-1} N)	8.8	16.1	8.3	13.6
REN (kg N 100 kg^{-1} N)	20.0	30.0	17.0	27.0
PEN (kg grain kg^{-1} N)	34.7	44.2	29.4	37.1
TFC (INR 10 ha^{-1})	23,055	34,930	31,059	34,274
GRF (INR ha^{-1})	24,578	28,014	22,316	25,274

Note: *AEN* agronomic efficiency, *REN* recovery efficiency, *PEN* physiological efficiency, *TFC* total fertilizer cost, *GRF* gross return above fertilizer cost

millet-wheat and pearl millet-mustard cropping systems also revealed large yield and economic advantages with the adoption of the SSNM. Thus, high net economic returns realized with implementation of the SSNM calls for large scale adoption of this technology to help reduce the gap between actual and potential yields at the farmer's field and experimental plots.

A another approach for SSNM is plant based which is a dynamic, farm-specific management of nutrients in a particular crop or cropping system using crop based estimates of indigenous nutrient supply for the better crop productivity. This approach tries to optimize the supply and demand of nutrients according to their differences in cycling through soil-plant systems. The approach was evaluated comprehensively for agronomic, economic and environmental performance in ~56 farmer fields with irrigated wheat and transplanted rice cropping system in the North-West India (Khurana et al. 2007, 2008). The results of the study clearly brought out the positive impact of SSNM on productivity and NUE under the rice-wheat cropping system (Table 3.2).

On an average, SSNM generated a grain yield of at least 0.9 (~17%) and 0.5 t ha^{-1} (~12%) in rice and wheat crops, respectively, compared with Farmers Practice (FP) in ~48% of the sites studied. At 21 of the total 56 farms studied, rice grain yield increases were >1 t ha^{-1} with SSNM compared with FP, while at 24 of the total 56 farms studied, wheat grain yield increases were >0.8 t ha^{-1}, showed the potential of the SSNM approach used. The another interesting fact observed was that the maximum increases in rice and wheat grain yields were obtained at sites with low fertility status of soils, while the regions with high fertility status of soils had minimum but significant increases in productivity of rice and wheat crops suggesting that blanket fertilizer recommendations are of limited use in tackling site-specific soil fertility management and that the adoption of site-specific strategies can give some impetus to the productivity growth of rice and wheat crops. Significant increases in NUE were achieved in rice and wheat through the field-specific N management practiced in the SSNM treatment. In general, compared with the FP, less fertilizer N was applied and AEN, REN, and PEN were significantly increased with SSNM. On an average, AEN was increased by ~83% (Khurana et al. 2008). However, crop productivity and NUE as an outcome of SSNM is certainly indicative of soil health enhancement for sustainable agriculture.

On the basis of long-term field experiment, results showed that the field-specific management of macronutrients increased yields of rice and wheat crops by ~12 and 17% and profitability by ~14 and 13%, respectively, in the North-West India. These results suggested that further increases in crop productivity can only be expected when farmers exploit the synergy that occurs when all aspects of crop, nutrient and pest management are improved simultaneously. They increased in nutrient uptake and NUE across a wide range of rice growing environments with diverse climatic conditions were related to the effects of IMPs and RMPs. A major challenge, however, is to simplify the approach for wider scale dissemination without sacrificing components that are crucial to its success (Singh and Bansal 2010).

3.12 Conclusions

Widespread multi-nutrient deficiencies and deteriorating soil health are the cause of low NUE, productivity and profitability. Compounded by this discouraging situation is the emerging problem associated with climate change influencing its impact on land use, soil quality, availability of irrigation water and use efficiency of resources and inputs, and crop productivity. As such, it provides a step in what needs to be a long-term process of scientific integration and stakeholder engagement, as the basis for developing better policies and IMPs, RMPs and BMPs along with FP. Adoption of precision technologies for more efficient use of resources and nutrients becomes more relevant in the current production scenario. While technological advancements, currently available, have the potential to address the issues when implemented in the right perspective of sustaining productivity and sustainability of the soil system on a long-term basis, the efforts also require addressing few issues connected with cataloguing of available information on soil variability systematically using modern tools of remote sensing, GPS and GIS. This provides opportunities to integrate crop based information for effective management of the field problems and dissemination. Sustainable production can be achieved through adoption of site-specific balanced and INM. Although SSNM proved to be useful in improving yield and NUE indicative of soil health enhancement per se, still the nature of the SSNM approach need to be tailored to specific circumstances under different climatic conditions. In some areas, SSNM may be site- or farm-specific, but in many areas, it is likely to be just region- and/or season-specific. Thus, a simplified future SSNM approach should combine decisions that are made on a site-specific basis as well as decisions that are valid for somewhat larger regions with similar agro-climatic conditions. The way we look at it, "Our Nutrient World" presents a major scientific, social and political challenge: to produce more food and energy for a growing world population, while simultaneously reducing the pollution threats on environment, climate and human health.

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Soil Mineralogical Perspective on Immobilization/Mobilization of Heavy Metals

4

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Abstract

Knowledge on the fate and transport of heavy metals is essential for predicting the environmental impact of metal contamination on agricultural soils. This chapter presents an overview of various factors that are involved in controlling the retention and mobility of heavy metals in soils with a special reference to soil mineralogy. The bioavailability of most elements, in particular heavy metals, in soils is governed by adsorption-desorption, complexation, precipitation and ion-exchange processes. The most important surfaces involved in metal adsorption in soils are active inorganic colloids such as clay minerals, oxides and hydroxides of metals, metal carbonates and phosphates and organic colloids. In addition to soil mineralogy, other important parameters controlling heavy metal retention and their distribution are soil texture, structure, pH, redox condition, cation and anion concentration, ionic strength, organic matter, microbial and root activity and climatic conditions. However, the ultimate fate of elements depends on a combination of several factors that are working together in the soil system. Finally, several remediation strategies have also been highlighted based on the fundamental principles of metal immobilization on mineral containing soil amendments.

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Heavy metals • Soil mineralogy • Adsorption • Desorption • Bioavailability • Metal immobilization

4.1 Introduction

The concern over the ever-growing imbalance in the natural environments has been increasing over the last few decades. Lately, the threat of toxicity of heavy metals to plants and humans has become manifold due to environmental contamination resulting from the extensive use of heavy metals in industry and agriculture. Since soils are, inadvertently, the ultimate victim of all human activities, it is extremely important for us to protect soils from being degraded in order to give future generations a safe and sound habitat. In the order of the abundance of various metals, Pb, Cr, As, Zn, Cd, Cu and Hg are found in the contaminated sites (USEPA 1996; Wuana and Okieimen 2011). The harmful effects of these metals in posing human and animal health issues are well known. Most of these metals impose serious risk due to their potential bioaccumulation and biomagnification in the food chain. Depending on their chemical speciation the metals can even migrate into the ground water and create a more serious issue.

More than one heavy metal can co-exist in contaminated soils. The bioavailability of the metals present in such multi-element environments is regulated to a large extent by the competition for available adsorption sites. In other words, the bioavailability and bioaccessibility of heavy metals depend on the elements' interaction with various soil components which control the metals' retention and mobility in soils. Studies have demonstrated that numerous physical, chemical, biological factors can be involved in controlling the retention and mobility of heavy metals. This chapter aims to present an overview on these factors in relation to the mineralogical properties of soils. Several remediation strategies have also been highlighted based on the fundamental principles of metal immobilization on soil minerals.

4.2 Adsorption of Heavy Metals on Soil Minerals

The fate and bioavailability of most elements, in particular heavy metals, in soils is governed by adsorption–desorption processes. Their adsorption on soils and minerals are also different due to their hydrolysis behaviour (Naidu et al. 1998). Among various heavy metals, Cu and Pb are reportedly the least mobile, whereas Cd and Zn are considerably more mobile. In addition, highly toxic metalloids such as As, Cr and Se, which exist as anions in the environment, are highly mobile because these anionic species get repelled by the intrinsically negatively charged soil particles.

The adsorption of heavy metals on purified soil clay minerals has been studied extensively in the past (Sen Gupta and Bhattacharyya 2012; Bhattacharyya and Gupta 2008; García-Sánchez et al. 1999). Several chemical modification processes were also known to increase the adsorption capacity of heavy metals on clay minerals (Bhattacharyya and Gupta 2008; Sarkar et al. 2010, 2012, 2013a; Rusmin et al. 2015; Perelomov et al. 2016; Celis et al. 2000). The surfaces of clay minerals contain two major types of reaction sites, namely Bronsted and Lewis acid sites, and ion exchange sites. This could be further explained by a constant capacitance model that assumes two kinds of binding sites (Schindler et al. 1987; Angove et al. 1998). The first type of adsorption sites adsorb metals by ion exchange, whereas the second type of adsorption sites involve inner-sphere binding to ampholytic –OH groups. The hydroxyl groups located on the edges (due to silanol and aluminol groups) are responsible for many metal–clay interactions. The 1:1 type clay mineral (e.g., kaolinite) contains a net zero layer charge, but the small negative charge at the broken edges can participate in metal adsorption. Contrarily, 2:1 type clay minerals (e.g., montmorillonite) hold a net negative charge of 0.8 unit per unit cell, which makes it a better adsorbent of heavy metal cations.

Adsorption reactions involving heavy metals are extremely rapid whereas desorption reactions can be orders of magnitude slower (McBride 1994). Additionally, adsorption–desorption reactions are often not completely reversible and this non-singularity or hysteresis can increase with increased residence time (or ageing) between the heavy metal and soil constituent surface (Glover et al. 2002; Rezaei Rashti et al. 2014). The adsorption–desorption of heavy metals on clay minerals depend on many environmental factors which consequently influence their mobility in soils. A complete understanding of the surface sequestration process in soils and minerals helps to better evaluate the bioavailability and potential toxicity of heavy metals.

4.3 Factors Affecting Retention of Heavy Metals in Soil

Mobility of heavy metal elements and subsequent retention in soil is controlled by a sequence of processes, beginning with desorption or dissolution followed by diffusion and convection. Further retention of elements at another location occurs due to re-adsorption or precipitation reactions. The key factors that control heavy metal retention in soils are summarized in Fig. 4.1. However, the ultimate fate of the element depends on a combination of several physical, chemical, biological and climatic factors.

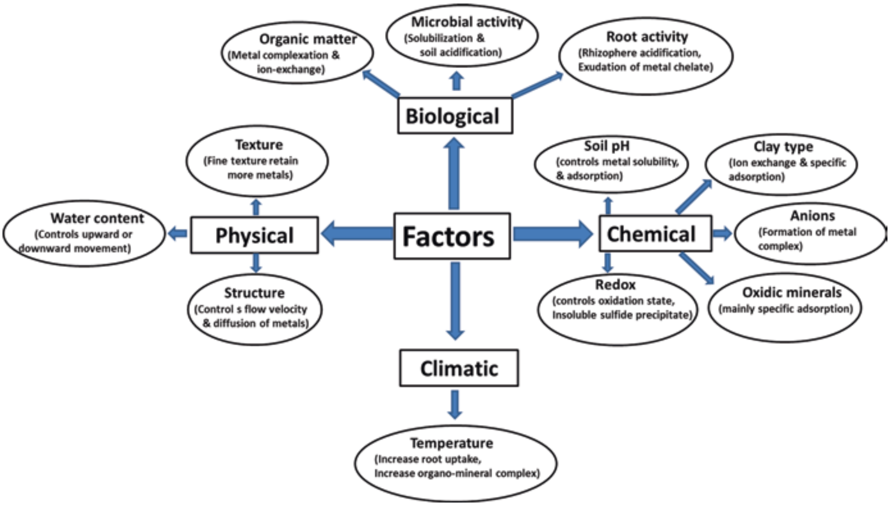

Fig. 4.1 Schematic diagram showing various factors affecting retention of heavy metals in soils

4.3.1 Physical Factors

4.3.1.1 Texture

Soil texture plays an important role in the retention of heavy metals in soils. Texture reflects the distribution of various particle size fractions including the fine particles like clay and oxidic minerals. In general, soils high in clay-sized minerals tend to retain a higher concentration of elements than coarse-textured soils, which is attributed to the higher surface area and metal binding sites of the clay-sized fraction. The importance of clays in the retention of metals was experimentally proved by several researchers. For example, Andersson (1979) demonstrated the strong adsorption affinity of Pb and other metals to the clay fractions and ranked adsorption affinity in the order of clay > silt > sand. Similarly, for a given total Cd concentration, Cd availability was higher in sandy soils than in clay soils (Eriksson 1989). In another study, the ammonium acetate extractable Zn, Pb, Cu and Cd was always lower in loamy soils than in sandy soils (Scokart et al. 1983).

4.3.1.2 Structure

The soil physical structures which may influence metal mobility include the properties such as fracturing and permeability (Jones and Jarvis 1981). This plays a crucial role in maintaining flow velocity into and out of soil aggregates which may be helpful to predict diffusion of metal ions within the soils. For example, soils with a higher macro porosity and colloids with greater surface charge contributed a higher degree of Pb mobility and transport (Karthanasis 2001). While the presence of earthworms that tended to increase soil porosity and diffusivity resulted in increased plant-available Pb and Zn concentrations (Ireland 1975).

4.3.1.3 Water Content

High solubility of heavy metals is not manifested as significant mobility unless there is sufficient water movement in the soil pores. Under arid climatic condition, the net water flow through the soil profile is upward and the mobile metals that are carried to the surface become concentrated by evaporation. Conversely, under wet condition, mobile metals are carried downward as long as there is free drainage. However, the mobility of elements is ultimately governed by the individual character of the particular elements. Agricultural sites that were subjected to the use of arsenate, lead and copper as pesticides many decades ago still retained Pb and Cu in the soil surface, although arsenate moved deeper in the soil profile in some cases (McBride 1994). Even under continuous leaching, removal of a large portion of these less mobile elements by natural process could take over thousands of years (McBride 1994).

4.3.2 Chemical Factors

4.3.2.1 Soil Reaction (pH)

Soil pH is generally considered to be the principal factor controlling elemental mobility. It governs elemental availability mainly by three ways: (1) by influencing the metal solubility; (2) controlling the precipitation–dissolution reaction, and (3) controlling the adsorption process. In general, the solubility of metals tends to increase at lower soil pH and decrease at higher pH values (Chuan et al. 1996; Ming et al. 2016). For metal cations, high pH would favor adsorption and precipitation as oxides, hydroxides and carbonates (Park et al. 2011a). Generally, in acidic pH, adsorption reaction becomes the important process in controlling elemental concentration in soil solution, whilst precipitation reaction takes the lead under alkaline conditions. Increasing solution pH tends to increase in the net negative charge of soil colloids and thus increases affinity of soils for metal cations (Naidu et al. 1998; Wu et al. 2003). The correlation between metal adsorption and pH is partly due to the competition of H^+ (and Al^{3+}) ions for binding sites at low pH leading to decreased metal adsorption (Basta and Tabatabai 1992).

4.3.2.2 Redox Condition

Soil redox potential is also crucial in controlling mobility of elements. Reduction–oxidation (redox) reaction is a process that involves flow of electrons from a reducing agent to an oxidizing agent. Redox reactions are governed by the free electron activity (pE) in soil solution, also expressed as Eh, the redox potential (Sposito 1983). High redox potential is recorded in well-aerated dry soils, whilst soils prone to waterlogging and high in organic matter content tend to have low Eh values. Some elements become more soluble and mobile in one oxidation state than another (e.g., Mn, Cr, As and Se) (Sarkar et al. 2012, 2013b). Transition metals (e.g., Fe, Mn) could facilitate the electron transfer reactions in the presence of organic acids and clay minerals to carry out reduction of metalloids (e.g., Cr) (Sarkar et al. 2013b). The elements that are classified as chalcophiles (e.g., Cu, Hg, Zn, Cd, As, Se and Pb) might form sulfide minerals in reducing environments which are insoluble in nature. The solubility of Pb, Cd and Zn could increase under reduced soil environment due to possible dissolution of Fe–Mn oxyhydroxides under reducing environments (McBride 1994). Under reducing environments Hg could form volatile organomercury compounds which might reduce soil bioavailability apparently.

4.3.2.3 Clay Content and Type

Heavy metals are less mobile in soils where a large quantity of binding sites for adsorption is available. Clay particles have surface functional groups that tend to adsorb heavy metal ions and make it immobile in nature. As described earlier, heavy metal adsorption can be described in two basic processes: nonspecific adsorption or ion exchange reaction and chemisorbed inner-sphere complex. Most phyllosilicate clay minerals such as vermiculite and montmorillonite carry permanent negative charge due to isomorphous substitution of cations within their mineral structure. A large portion of the metal binding capacity are due to the permanent and/or pH-independent charge. Further, cation adsorption by expandable layer silicates might occur largely in the inter-layer surfaces compared to the planar surfaces. However, penetration of water and metal cations between the layers of non-expandable phyllosilicates (e.g., kaolinite and serpentine) is difficult due to their low cation exchange capacity (Bhattacharyya and Gupta 2008).

4.3.2.4 Oxidic Material Content

Oxides and hydroxides of Fe and Mn occur in association with clay minerals as coatings on the phyllosilicates and also as crystals or free gels. Oxides concentrations are usually low under reducing conditions; therefore, influence of oxidic materials in controlling metal solubility is likely to be important under oxidizing environments. Hydroxides of Mn and Fe may reduce heavy metal ion concentration by both surface adsorption and precipitation reaction (Chuan et al. 1996). Surface adsorption on oxidic minerals followed by diffusion of metal ions into the small pores of mineral lattice structure might also contribute in elemental retention in soils (Backes et al. 1995). Preferential adsorptions of metals by different oxides are governed by the type of adsorbing surfaces and also by type of elements. For example, the preferential order of specific adsorption by hydrous oxides follows the order of Pb > Cu >> Zn > Cd. Oxides of Mn particularly have a strong affinity for Pb adsorption as compared to Cd. Further, Zn and Cu are probably adsorbed with equal affinity by Mn- and Fe-oxides. When multiple metals are present in the soil solutions, they might impart competition to each other for the active surfaces on clay minerals, and consequently one metal could become more mobile than the other (Ming et al. 2016).

4.3.2.5 Anions

Concentration of anions in the soil solution also controls the heavy metal solubility in soil. It is well established that various inorganic and organic anions form complexes with heavy metals and thus influences the metal solubility and subsequent mobility in soil. Precipitation of stable metal complex is governed by the type of anions present in the soil solution. For example, the mobility of Pb ions reduced in the presence of sulfate and phosphate anions due to the formation of sparingly soluble salts between Pb and these anions (Park et al. 2011a).

4.3.3 Biological Factors

4.3.3.1 Organic Matter

Organic matter affects the physical, chemical and biological conditions of soils. Decomposition of plant and animal residues leads to accumulation of organic matter in soils. Soil organic matter is composed of various functionally active compounds such as humic acid, fulvic acid and humin which are typically associated with soil inorganic colloids such as clay minerals. Organic matter reacts with heavy metals mainly by two major processes, including complexation or inner-sphere mechanism and adsorption or ion exchange reaction (Evans 1989). The active functional groups of organic matter are the negatively charged carboxyl, phenolic and amino groups that are involved in cation-binding reaction. These functional groups increase in number with the increase in humification processes. The increase in pH tends to increase in ionization of functional groups and organo-metal complexes thus become stable at higher pH values (Krishnamurti et al. 1997). There were also evidences where organic matter formed soluble organo-mineral complexes especially when organic component was dominated by the fulvic acid fraction (Temminghoff et al. 1997).

4.3.3.2 Microbial Activity

Microorganisms are considered to be the most important component controlling the biological activity in soils and influence the nutrient recycling in the system. Various functions are served by microbial transformation of metals. Generally, microbial transformation of metals is classified into two main categories: redox transformation of inorganic forms and transformations from inorganic to organic form, and vice versa (Bolan et al. 2013). Through oxidation of Mn, Fe, As and S, microorganisms can obtain energy. On the other hand, through dissimilatory reduction processes they can utilize metals as a terminal electron acceptor for anaerobic respiration. Soil microorganisms might also immobilize heavy metals by aiding the precipitation of hydrated ferric oxides and sulfides and also by exudation of metal complexing mucopolysaccharides (Park et al. 2011b). Bacterial cell walls may adsorb heavy metals from soil solutions due to the presence of surface functional groups (Mullen et al. 1989). Sometimes microorganisms might enhance metal solubility by the acidification of the soil (Ernst 1996).

4.3.3.3 Plant Root Activity

Plant root also plays an important role in controlling the metal bioavailability (Krishnamurti et al. 1997; Ernst 1996). The exudation of acidic chemicals (e.g., H_2CO_3) lowers the rhizospheric pH and hence increases metal bioavailability. Plant roots are also known to release chelating organic molecules that tend to solubilize metal cations from its insoluble forms, which results in greater bioavailability of metals in the solution. Further, symbiotic association of fungi with plant roots might facilitate metal solubilization over a large soil area.

4.3.4 Climatic Factors

Heavy metal uptake by plant roots was found to be positively correlated with temperature (Miller and Friedland 1994). This relationship was attributed to the increase rate of organic matter decomposition at higher temperature, which increased the mobilization of organo-metal complexes. Moreover, with an increase in temperature, the metal activity in the soil solutions and in plant roots might increase the absorption rate. Further, high evapo-transpiration rate at higher temperature also might contribute to an increased uptake of metals by plants.

4.4 Stabilization/Immobilization of Heavy Metals in Soils

The key mechanisms of immobilization of heavy metals in soils are adsorption, surface complexation, precipitation and ion exchange (Fig. 4.2). These are achieved by applying various amendments to the contaminated soils (Table 4.1). One of the most effective physico-chemical processes controlling the behavior and bioavailability of heavy metals is adsorption (Wan Ngah and Hanafiah 2008). A charged solute (ions) can get attached to the charged soil surface due to electrostatic interaction (Bolan et al. 2003). This strategy of immobilization involves the addition of adsorbents (e.g., clay minerals, zeolites, fly ash, red mud and biochar) into the contaminated soil (Wuana and Okieimen 2011; Sarkar et al. 2012; Antoniadis et al. 2012; Taghipour and Jalali 2015; Usman et al. 2005; Zhang et al. 2016). The adsorbent can also provide surface complexation reaction. Through this reaction metals are redistributed from solution phase to the solid phase and reduce their bioavailability in the environment (Bolan and Duraisamy 2003). In this method, functional groups like hydroxyl, carboxyl, amino and phenoxyl on the surface of organic matter or clay minerals react with heavy metals and produce surface complexes (Harter and Naidu 1995). These complexes are of two types: (1) inner-sphere complexes, in which no molecule of the solvent is interposed between surface functional groups and ions, and (2) outer-sphere complexes, in which at least one molecule of the solvent comes between the surface functional groups and ion (Alloway 1995; Bolan et al. 2014). The outer-sphere complexes are less stable than inner-sphere complexes. Precipitation of heavy metals is another way to reduce metal bioavailability in soils. Precipitation can be achieved by adding various binding agents (e.g., cement, biochar, fly ash, lime, zeolite, manure, compost, chitosan and sewage sludge) (Bolan et al. 2014; Ling et al. 2008; Wuana and Okieimen 2011; Xi et al. 2014). Precipitation of hydroxides or sulfides within the solid matrix is one of the major mechanisms by which metals can be immobilized (Fu and Wang 2011). Hydroxide precipitation is relatively effective in the pH range of 8–11 (Huisman

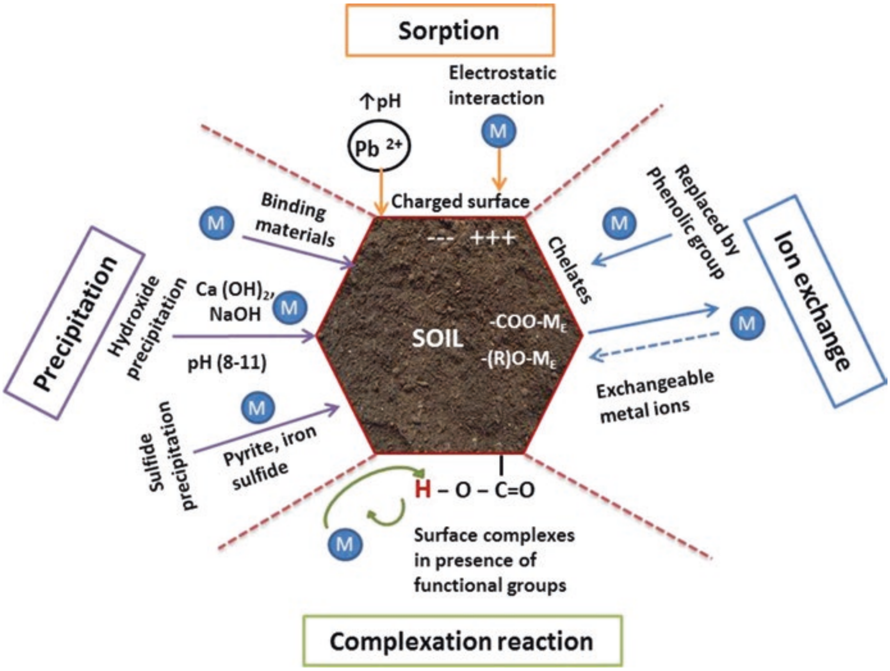

Fig. 4.2 Schematic diagram representing different immobilization/stabilization processes of heavy metals in soil

Table 4.1 Soil amendments for heavy metal immobilization

Materials	Sources	Heavy metal immobilized
Lime	Lime factory	Cd, Cu, Ni, Pb, Zn
Phosphate salt	Fertilizer plant	Pb, Zn, Cu, Cd
Hydroxyapatite	Mining of phosphate rock	Zn, Pb, Cu, Cd
Fly ash	Thermal power plant	Cd, Pb, Cu, Zn, Cr
Slag	Thermal power plant	Cd, Pb, Zn, Cr
Red mud	Aluminum industry	Zn, Cu, Cd
Clay minerals	Mining industry	Cd, Pb, Cu, Zn, Cr, As
Zeolites	Mining industry	Zn, Cd
Fe/Mn oxides	Oxidic minerals	Cd, Pb, Cu, Zn,

et al. 2006). Ion exchange is another way of remediating heavy metals in soils (Dabrowski et al. 2004). In this method, metal cations are replaced by surrounding phenolic groups, finally forming a chelate. The ion exchange agent could be naturally occurring inorganic zeolites or synthetically produced organic resins (Vazquez et al. 1994). However, this is a reversible process. Depending on the type of functional groups of exchanging ions, ion exchanger can be strongly acidic (sulfonate), weakly acidic (carboxylate), strongly basic (quaternary ammonium) and weakly basic (tertiary and secondary amines) (Hubicki and Kołodyńska 2012). Remediation

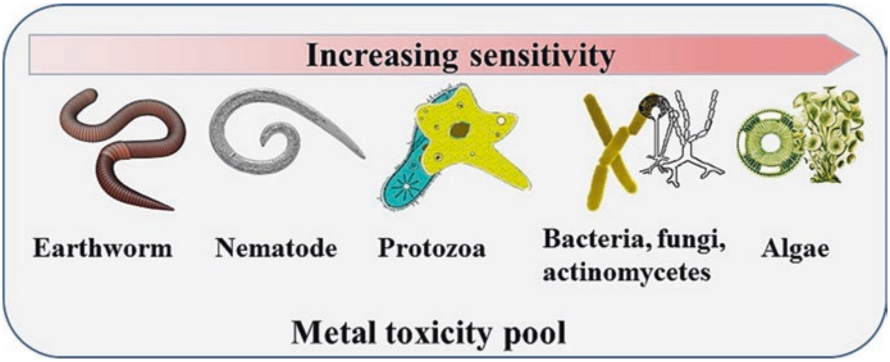

Fig. 4.3 A generalized schematic presentation of different level of toxicity of metals on various soil biota (adapted and modified from Vig et al. 2003)

of heavy metal contaminated soils with various organic and inorganic amendments has attracted attention due to the method's low cost and environmental benefits.

4.5 Biological Quality of Metal Contaminated Soils

Metals can impose highly toxic effect on the native microorganisms in soils. The microorganisms also need metal ions at very low concentration for their nutrition. However, an excess amount of these essential metals can be detrimental for their cellular functions (Lemire et al. 2013). In a soil microhabitat, the degree of metal toxicity to microorganisms depends primarily on the types of metals, their speciations and the microorganisms themselves (Giller et al. 1998). A generalized toxicity profile of heavy metals represents that microorganisms (e.g., algae, bacteria, fungi, actinomycetes and protozoa) are more vulnerable to metal toxicity than the macrobiota (e.g., nematode and earthworm) (Fig. 4.3) (Vig et al. 2003). This chapter mainly emphasizes on the microorganisms due to their major role in the dynamics of soil biogeochemical processes in agricultural and environmental remediation perspective.

The heterogeneity of soil largely controls whether the toxicity of metals is mitigated or not. As described earlier, numerous factors including soil pH, organic matter and mineralogical composition are involved. Clay minerals and some of their modified products are efficient adsorbents of toxic metals in soils. This reduces metal bioavailability to the microorganisms and saves them from toxicity (Biswas et al. 2015; Mandal et al. 2016). In soils, the microorganisms often tend to nest with or in the vicinity of clay minerals and form micro-aggregates or biofilms (Almås et al. 2005; Biswas et al. 2017; Giller et al. 2009). Therefore, the application of clay minerals (as amendments) can be an efficient supplement in soil microsites to protect the microbial cells from toxic metals.

However, the efficiency of a clay-based adsorption technique mostly lies on the properties of the clay mineral for a target toxic metal. Álvarez-Ayuso et al. (2003)

reported that a 4% palygorskite amendment in a mining soil (pH = 5.4) immobilized 92% of the mobile (soluble and exchangeable) Pb, 77% of Cu, 76% of Zn and 48% of Cd. Several other clay minerals and zeolite were also used as the metal-immobilizer in soil; however, how the addition of clay minerals into soil would impact the microbial community and thus the overall microbial quality remained inconclusive. It was found that the toxicity of Cu (in terms of substrate-induced nitrification and substrate-induced respiration) could not be explained by the soil solution metal concentrations or exchangeable metal concentrations, but a significant relationship was found between the EC_{50} values for substrate-induced respiration and percent clay content (Broos et al. 2007). Therefore, it is highly important to conduct field scale studies in the toxicological perspective for the quality of soil biota while a raw and modified clay products is used as the metal adsorbent.

4.6 Conclusions

The fate and behavior of heavy metals and metalloids in the soil environment are governed by numerous physical, chemical and biological factors. The key physico-chemical properties that control heavy metal retention in soils are imparted by the clay minerals and oxidic particles. Additionally, organic colloidal particles also play an important role. The mineral and colloidal particles have numerous active sites on their surfaces which can retain heavy metals through adsorption, complexation, precipitation and ion exchange. Due to these properties mineral amendments can be applied to contaminated soils alone or in combination with another organic amendment for immobilizing heavy metals. This can be one of the cost effective strategies for heavy metal remediation in contaminated soils. However, further research is needed to investigate the bio-physico-chemical interactions of heavy metals where microorganisms also play a key role in the biogeochemical cycle of elements in soils.

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Using Laboratory Analysis to Inform Adaptive Management

5

Simon W. Leake and Alisa Bryce

Abstract

Soil and plant analysis is a tool of critical importance to the management of soil based production systems. Management by use of visual crop symptoms alone is retrospective, as by the time visual symptoms are present production has already been seriously compromised and biomass yields reduced.

The modern soil laboratory is pivotal to informing the soil manager what adaptive practices are needed to address chemical and physical imbalance before they occur. The most reliable analysis is calibrated against crop trials, to the plant variety level, in a particular soil type (Asher et al. 2002). Yet despite the fact that thousands of such field experiments have been conducted, there remain gaps for regions and species, and the information itself is out of reach for many soil managers. Thus, in the absence of correlated field trials soil managers are very often faced with making informed judgments from the laboratory data they have at hand.

Soil testing may be used for pre-emptive purposes (pre-plant or benchmark analysis), routine monitoring to identify soil change (particularly fertility decline), monitoring in field trials (usually to help explain results) or for diagnostic purposes (specifically, deficient element analysis).

Plant tissue analysis adds a further layer of explanatory data, confirming deficiencies evident in soil analysis.

Different test methods and demands on accuracy and precision apply to the different soil and plant testing purposes. A basic laboratory capable of assessing most soil and plant tissue needs can be set up quite cost effectively with only seven key pieces of equipment, plus ancillary equipment (acids, extraction agents, glassware, etc.).

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Soil and plant tissue analysis is not only relevant to the agricultural production manager, but also for rehabilitation, and in the urban context such as greenhouses and hydroponics. The effective use of laboratory data is the single-most important tool for adapting soil management practices to the production situation.

Keywords
Soil analysis • Plant tissue analysis • Laboratory • Instrumentation • Benchmarking

5.1 Introduction

Soil and plant tissue analysis are tools of critical importance to the management of soil based production systems. Management by use of visual crops symptoms alone is reactive. Therefore, the pre-emptive use of laboratory analysis is of prime importance for soil productivity.

Unfortunately, most of the world's agricultural management is still reactionary, waiting for obvious yield declines to occur before action is taken to identify the reasons. The modern soil laboratory is pivotal to informing the soil manager what adaptive practices are needed to address chemical and physical imbalance before they occur. This is just as true for the farmer and agronomist as it is for mine site and rehabilitation advisors. Without the use of laboratory data, experiments and/or factorial trials are the only way to ascertain the primary weaknesses in the production system. These processes are usually slow and costly. Use of laboratory data can greatly speed up and reduce the cost of such empirical trial work, or even render it unnecessary.

The most reliable soil analysis is calibrated against crop trials, to the plant variety level, in a particular soil type (Asher et al. 2002). Despite the fact that thousands of such field experiments have been conducted, the agronomist and pedologist, most often, is faced with the necessity of making informed judgments from the laboratory data they have at hand. In the great majority of cases, the world's farmers use only their own observations in an attempt to adapt their practices to a perceived reduction in crop vigor or rehabilitation result. These observations may include soil colour, texture, crusting, hardness and crop symptoms. Since subtle nutrient deficiencies and imbalances cannot be seen, waiting for crops to become symptomatic under extreme deficiency represents a significant loss of production.

The analysis of soils is an empirical and inexact science; however, it is not difficult to recognize degraded and deficient soils using standard laboratory methods and to use the results to make recommendations for soil improvement.

Soil testing may be used for pre-emptive purposes (pre-plant or benchmark analysis), routine monitoring to identify soil change (particularly fertility decline), for monitoring field trials (usually to help explain results) or for diagnostic purposes (specifically, deficient element analysis). Different test methods and demands on accuracy and precision apply to these different purposes.

Plant tissue analysis adds a further layer of explanatory data to many analytical investigations. In all cases of soil/plant nutrient pathology diagnosis, both soil and plant tissue analysis is necessary to fully understand both the symptoms and their cause.

Only in well-known regional production systems, where the soil types are known, and experienced agronomists have access to past analytical testing it is possible to rely on judgmental decision-making. However, it is not possible to reliably adapt management practices to a particular soil/plant relationship without access to the modern agricultural laboratory.

Commercial soil laboratories are traditionally agricultural based, originally catering for agronomists to help advise on fertilizer recommendations. As such the range of analytical services offered are somewhat restricted and they mostly do not cater for the full range of "soil science" investigations. Traditionally also, they do not offer much in the way of physical analysis, such service requirements being filled by geotechnical and engineering laboratories.

The other branch of laboratory science that has been aided by the establishment of environmental monitoring and regulation is that offering contamination and other environmentally related analysis.

In this chapter, a range of laboratory services are suggested and discussed in detail. These services are required to diagnose soil and plant health related issues rather than soil engineering or environmental health concerns, although there is some obvious overlap of the test methodologies.

5.2 The Role of Soil and Plant Analysis

The purpose of plant and soil analysis is to diagnose or confirm nutrient deficiencies or toxicities. All organisms are fundamentally built from the same ingredients. Carbon (C), hydrogen (H), nitrogen (N), oxygen (O), phosphorus (P) and potassium (K) make up more than 80% of most living beings. Plants and animals largely require the same elements, with a few differences.

5.2.1 Elements Needed by Plants

Plants need about 16 elements to fulfill their growth and reproductive needs. Carbon, hydrogen and oxygen they get from either the atmosphere (CO_2) or water (H_2O). The rest plants extract from the soil. Note that N is the anomaly here, as it enters the soil system via micro-organisms—either free living or symbiotic with plants—that take N from the atmosphere and convert it into plant-available N. The macronutrients N, P, K, sulphur (S), calcium (Ca), magnesium (Mg) and sodium (Na) are required by plants in greater amounts, whereas the micronutrients—manganese (Mn), copper (Cu), iron (Fe), zinc (Zn), boron (B), chlorine (Cl), nickel (Ni) and molybdenum (Mo) are required in minor or "trace" amounts.

Yet each element is as important as the next, meaning a deficiency in any one of the elements, including Mo which is the trace element required in the smallest amount, affects the utilization of other nutrients inhibiting plant growth, productivity and yield. This phenomenon is known as the "limiting factor".

Table 5.1 below outlines the elements needed by plants.

5.3 Field Analysis and Diagnosis

The first step in adaptive soil management is to physically check the status of the soil and plants in the field.

5.3.1 Soil

A few simple, in-field soil tests can be revealing of a range of soil problems.

Soil Texture—influences the physical and chemical properties of a soil. The greater the proportion of clay in a soil, the better the soil will retain nutrients (clay mineral type dependent), and water. Sandier or "lighter" soils have lower cation exchange capacity (CEC) and are more susceptible to leaching. Heavier soils (clay) have a greater water holding capacity, and are more susceptible to compaction.

pH—indicative of what nutrients are likely to be unavailable or toxic. For example, at acidic pH's aluminium can be toxic. When tested in water, when soil pH <5.4, aluminium or manganese can be toxic, and the soil can have molybdenum deficiencies. Microbial activity is also reduced at very low or high pH. A pH meter, Raupach test kit or test strips are required to test pH in the field.

Electrical conductivity (EC)—indicates whether salt levels may be affecting plant growth. The higher the EC, the higher the amount of salts present in a soil. It is important to know the soil texture to understand soil salinity, as texture affects the degree to which salt will affect plant growth. The sandier the soil, the greater the effect. The EC 1:5 in water analysis method, using an electrical conductivity metre, is not a true indicator of salinity—rather it underestimates it. To get a true estimate, multiply the 1:5 dS/m value by a texture based conversion factor. This is known as ECe. Alternatively a saturated paste extract can be made but it is time consuming and tedious to get enough of this water out of the paste to measure the true ECe.

Dispersion—is assessed by gently placing a few small (1–3 cm^2) air dried aggregates into deionised water, potable water or, if irrigating, into the irrigation water used. The behaviour can be scored according to the Emerson scale.

Dispersibility	Emerson aggregate classes
Very high	1, 2 (3)
High	2 (2)
High–moderate	2 (1)
Moderate	3 (4) and 3 (3)
Slight	3 (2), 3 (1) and 5
Negligible	4, 6, 7, 8

Source: Hazelton and Murphy (2007)

Table 5.1 The role of essential elements in plants

Element	Function in plants
Carbon	Building block of proteins, amino acids, carbohydrates, etc.
Hydrogen	Required to build sugars. Creates a proton gradient to drive the electron transport train for photosynthesis and respiration
Oxygen	Required for cellular respiration
Nitrogen	Needed for all growth processes. Found in all plant cells, proteins, hormones and chlorophyll
Phosphorus	Has a key role in energy storage and transfer. Necessary for all growth processes, including nitrogen fixation
Potassium	Needed for a wide range of important processes within the plant, including cell wall development, flowering, seed set and photosynthesis. Potassium has a key role in osmo-regulation and the flow of nutrients in the sap stream. It helps legumes fix N and also improves resistance to stress from weather, insects and diseases
Sulphur	Required for the formation of several amino acids, proteins and vitamins and for chlorophyll production
Calcium	Involved in the proper functioning of growing points (especially root tips), maintaining strong cell walls and seed set in clovers
Magnesium	An essential component of chlorophyll and is required for the transport of phosphorus around the plant
Manganese	Has several plant growth functions. It is closely associated with Fe, Cu and Zn as a catalyst in redox reactions; is essential for rapid germination and plays a role in enzyme systems
Copper	Required for the formation of enzymes for chlorophyll production, nutrient processing and the plant's exchange of water and oxygen for carbon dioxide
Iron	Associated with the production of chlorophyll and helps to carry oxygen around the plant cells. It is also involved in reactions that convert nitrates to ammonia
Zinc	Associated with the formation of chlorophyll and of several enzyme systems required for protein synthesis. It also has a regulatory role in water intake and use efficiency
Boron	Largely involved in moving sugars throughout plants, and seed production in legumes. Is involved in the uptake and efficient use of calcium in the plant
Sodium	Non-essential element but can be used in chlorophyll synthesis in the absence of K (Maathuis 2014)
Chlorine	Thought to stimulate carbohydrate metabolism, some plant enzymes, chlorophyll production and the water holding capacity of plant tissues
Molybdenum	Essential for the health of the rhizobia bacteria nitrogen fixation. It is also directly involved in N metabolism and specifically implicated in the electron-transfer system (for example, nitrate reductase and enzyme nitrogenous reactions). Used by enzymes to carry out redox reactions (Kaiser et al. 2005)
Selenium	Helps counteract abiotic stresses such as frost, drought and salinity (Feng et al. 2013)
Cobalt (Co)	Not essential for all plant growth, however, Rhizobium (N-fixing) bacteria in legumes require it
Nickel (Ni)	Essential for conversion of urea to ammonium

For more detail see Reuter and Robinson (1997), Handreck and Black (2010) and Marschner (2012)

Colour—indicates the types of minerals present, the degree of oxidation or waterlogging, and organic matter levels. Iron produces a red colour, and the redder a soil the more oxidized the iron is, i.e. the more aerobic the soil. Waterlogged soil is often mottled, and dull coloured. Grey, green and blue soils are often indicative of hypoxic conditions. Light grey/white soils, if not waterlogged, indicate leaching and soil poverty. Organic soils are blacker.

The *smell* of a soil gives clues to the degree of oxidation or reduction at depth. Poorly aerated soil will smell “rotten”, while well-aerated soil has the earthy smell of actinomycetes—the soil microbes that cause the smell.

Soil structure indicates whether a soil is compacted, likely to be sodic (>6% exchangeable sodium), and likely permeability. Soils with a platy or massive structure are often compacted, with low permeability. Columnar peds suggest sodicity. Granular structure is often highly permeable; while blocky, columnar or prismatic structures often have moderate permeability.

Manganese inclusions are recognized as black nodules in a soil. They are indicative of periodic waterlogging. Mn is confirmed by dropping hydrogen peroxide (H_2O_2) onto the nodules—if they fizz, then they are manganese.

Carbonates are white and fizz when exposed to hydrochloric acid (HCl). Carbonates indicate a soil is more likely to be alkaline.

Using the nine relatively simple tests above the following can be inferred about a soil:

1. Ability to hold nutrients
2. Likely nutrient deficiencies and toxicities
3. Water holding capacity
4. Likely drainage capacity (if not compacted)
5. Susceptibility to compaction
6. Waterlogging
7. Microbial numbers (organic matter)
8. Hardsetting, crusting and dispersion risk
9. Salinity levels

5.3.2 Plant

Soil nutrient deficiencies and toxicities cannot be seen in the soil itself, but make themselves known via the plants growing in them. Stunting, mottling, chlorosis, leaf drop, etc., are symptoms of a variety of nutrient imbalances. Nutrient deficiencies and toxicities vary in their symptoms from plant to plant, and are only visually evident once a severe state is occurring (Marschner 2012). Additionally, waiting for symptoms to become evident means deficiency is already occurring and yields are decreased. Using these symptoms, therefore, is a reactive approach, but can help supplement laboratory analysis when benchmarks are being defined.

Nutrient antagonism is the competition for uptake by plants. Excess of one nutrient can inhibit the uptake of others. Table 5.2 lists some of these interactions. The

Table 5.2 Rough guideline of nutrient deficiencies, toxicities and antagonism

	Deficiency	Toxicity	Antagonism
N	Older leaves yellow, and plant is stunted	Dark green leaves, succulent growth. Can cause Ca deficiency	Excess reduces P, Ca, B, Fe and Zn uptake
P	Leaves and stem can become red. Plant generally stunted	Shows up as deficiency of Zn, Fe or Co	Excess reduces Zn uptake. Antagonistic to B in acid soil
K	Spotted, mottled or curled lower leaves. May look like N deficiency as plants ability to utilize N is inhibited	Inhibits N use, and may affect uptake of Ca and Mg	Reduces Mg uptake
Ca	Highly variable symptoms, but often physiological disorders of fruits and vegetables, e.g. rotting fruit, weak stems, premature drop	Causes high pH which makes traces nutrients less available	B, Mg. High pH induces B, Cu, Fe, Mn and Zn deficiency
Mg	Whitish patches appear on older leaves and between leaf veins	Browning of veins, may have small necrotic spots on older leaves	
S	Rarely deficient. New leaves yellow	Rare	
Fe	Normally on younger leave first. Interveinal chlorosis that begins at leaf edges and works its way in	Rare	Mn
Mn	Younger leaves affected first. Veinal chlorosis	Leaves have crinkly edges. More common in strongly acid conditions	Fe
Cu	Veinal chlorosis, soft leaves, branches and stems	Often appears as Fe deficiency	Mo, and to a lesser degree Fe, Mn and Zn deficiency
B	Puckered leaves, distorted growing tips	Yellowing leaf tips followed by necrosis	
Zn	Older leaves yellow and may have stripes. Interveinal chlorosis. Zn deficiency often associated with Mn deficiency	Wilting and stunting of older leaves. Interveinal chlorosis	Fe, Mn

For further information see Bennett (1993), Reuter and Robinson (1997), Handreck and Black (2010) and Marschner (2012)

element in the antagonism column is inhibited by excess of the element listed in the first column.

Understanding the expected *rooting depth* for a crop provides a benchmark. Inhibited root depth may be caused by poor nutrition, lack of oxygen at depth, water imbalance, compaction or aggressive subsoil conditions (e.g. sodic, strongly acid/alkaline). Careful excavation of a soil profile is required to check root depth as roots can be torn during the exercise.

Healthy roots have white growing tips. Black root tips and rotten roots indicate disease and/or waterlogging.

Each region and crop will have diseases, whether bacterial, fungal or viral, that make an appearance each season or year. While disease diagnosis and treatment is not within the scope of this chapter, stressed plants are more susceptible to disease than healthy plants. Root disease can manifest as nutrient deficiency, as roots are unable to take up the nutrients required.

5.4 Laboratory Analysis and Diagnosis

Access to reliable laboratory services is critical to the optimization of soil management and to tracking and responding to soil change in agroecological systems. Equally important is the experienced soil scientist or agronomist whose role is to interpret the results and make positive responses or adaptations of the management systems.

Unfortunately, such access is not universally available in the developing world. Even in the developed world the centralization of laboratory resources by the big fertilizer companies does not always lead to better long-term adaptation of soil management, instead focusing on short-term, often single crop cycle, returns.

Experience in Australia was that the initial investment in agricultural laboratory assets was made by public institutions such as departments of agriculture and universities, mainly to support the research effort. These then evolved to provide extension services and were, for the most part, replaced by the large laboratories operated by fertilizer manufacturers during the 1970s and 1980s. Independent laboratories now make up a small proportion of the agricultural testing market focusing instead on environmental analysis. In the USA the pattern was somewhat different with several large, high volume, independent laboratories servicing most of the agricultural market.

Even cursory searches of the internet suggest that most of the laboratory effort in large countries such as India, China and Nigeria is at the stage where public institutions and their off-shoots provide the majority of laboratory services.

As well as some basic laboratory instrumentation, well-trained and experienced staff are required for the establishment of a diagnostic agricultural laboratory.

5.4.1 Instrumentation

A simple but powerful diagnostic laboratory, able to perform the great majority of agricultural soil and plant diagnosis, can be established with the following equipment (Table 5.3).

With some intelligent shopping, especially from the second hand marketplace and over the internet, the basic laboratory equipment of this type could be purchased for around 75,000–110,000 USD.

Table 5.3 List of basic laboratory equipment and associated analyses

Equipment	Infrastructure support/ spares	Analytes measured
Universal pH indicator	Resupply	Crude screening pH testing, soils, waters
Glass electrode pH meter	120/120/240 V AC supply, new probes	pH H_20. pH $CaCl_2$, acid/base titration
Electrical conductivity meter	120/240 V AC supply, cleaning agents	Salinity of soils and waters
Manual spectrophotometer	120/240 V AC supply, glass or plastic cuvettes	All metals from Table 5.1 except Na and K. Cl, P, S, NO_3, NH_4, alkalinity of waters, CO_3, I. Chlorophyll a and b
Flame photometer (alternatively use the Flame AAS)	120/240 V supply, bottled propane or butane. Cs as ionization suppressant	Na and K
Flame atomic absorption spectrophotometer	120/240 V AC supply, acetylene gas, compressed air. Replacement hollow cathode lamps	All metals from Table 5.1. May not have sensitivity for Mo without add on techniques such as isothermal ionization and hydride generator
Temperature controlled hotplates/digesters	120/240 V AC supply	Acid digestion of plant and soil samples for "total" elemental analysis. Kjeldahl N, organic carbon
Ancillary equipment: – Weighing balance 300–0.03 g – Inventory of glassware including volumetric – Inventory of laboratory chemicals, extraction agents, acids, alkalis, standards, reagent chemicals	External calibration reference materials Certification of purity	Universal for all testing

Note: Experience is that local electricity supplies often do not conform with the expectations of instrument manufacturers. A robust stabilizer feeding a UPS is often needed. This was certainly the case in Hanoi according to Milham (Paul J. Milham, Adjunct Fellow, Hawkesbury Institute for the Environment and the School of Science and Health, University of Western Sydney, LB 1797, Penrith, New South Wales 2751, Australia, personal communication)

In a more capital intense laboratory with good industrial support infrastructure and with a need for higher throughput, larger sample numbers and/or lower detection limits, the following three instruments are required (Table 5.4).

The cost of this highly sophisticated instrumentation has been reducing steadily for the 20 years since they became standard in agricultural laboratories. An ICP OES or ICP MS with ancillary gases and refrigerated water will cost something between 60,000 and 200,000 USD.

Table 5.4 Laboratory equipment for large sample volumes and lower detection limits

Equipment	Infrastructure support/spares	Analytes measured
Inductively coupled plasma-arc spectrometer with auto-sampler	120/240 V AC supply, purified argon gas, dried compressed air. Replacement nebulizers, torch, Si pump tubing, plastics. Good access to servicing	P, S, Na, Ca, Mg, Fe, Zn, Cu, B, Mn, Si, Al. Most contaminant heavy metals
Inductively coupled plasma-arc mass spectrometer with auto-sampler	120/240 V AC supply, ultra-purified argon gas, dried compressed air. Replacement nebulizers, torch, Si pump tubing, plastics. Clean-room facilities	As above at lower detection plus Se, Mo, Co
C, N and S dry combustion methods	120/240 V AC supply, purified oxygen and helium. Good access to servicing	Total C, N and S

5.4.2 Methods

5.4.2.1 Soil Analysis

There is a bewildering array of test methods in the soil science literature, and every country and region has their own preferences and prejudices. Sometimes this is based on fertilizer and yield response trial work on particular soils and crop types, often it is simply based on custom and experience.

It is beyond the scope of this chapter to discuss the types of methods or the details of test methods. The Further Reading section provides some examples of the recommended test methods in selected regions. Readers are encouraged to research the most applicable test methods for particular crops and soil types in their area.

The following general recommendations are made:

- Use of universally applicable SI metric system of units. The imperial and US systems are more difficult to calculate with.
- Do not use the archaic oxides units for the major elements (P_2O_5, K_2O, etc.). It may be of interest historically but adds no chemical meaning, creates an unnecessary difficulty to calculation and consequently has no place in modern fertilizer and chemical science.
- Do not be afraid to modify methods to streamline the steps, reduce labour and cost. Many methods originate from research institutions and can be unwieldy and laborious. They can usually be miniaturized saving reagents and space. Validation of the changes is necessary so that any loss of accuracy or precision is quantified and acceptable.

The most common test types offered by soil, fertilizer and nutrient laboratories are summarized in Table 5.5.

All these tests can be used to benchmark soils, make fertilizer and ameliorant recommendations, monitor soil changes in response to cropping regimes or identify degradation due to mining, erosion or other disturbance. A key benefit of soil testing

Table 5.5 Common test types offered by soil laboratories

Common test types	Purpose
pH in water	Assess pH limitations, estimate liming or acidification requirements
pH in $CaCl_2$, $BaCl_2$ or KCl	Assess pH limitations, exchangeable acidity, estimate liming or acidification requirements
Electrical conductivity	Assess salinity and background nutrient strength
Cation exchange capacity and exchangeable cation ratios	Assess soil degradation, comparison with ideal ratios, sodicity, exchangeable acidity and aluminium. Recommendations for gypsum, lime, dolomite, potassium and magnesium requirements
Available P	P fertilizer requirements, P induced trace element deficiency
Available and total N	Indices of N availability, C/N ratios
Available metallic trace elements Fe, Mn, Zn, Cu	Assessing potential trace element deficiencies and toxicities
Available B	Assessing B deficiency and toxicity
Mo	Needs for Mo fertilizers to prevent deficiency and for N fixing bacteria
Se, I, Co	Assessing potential human/animal nutritional requirements
Total organic carbon	C/N ratios and soil OM monitoring

is that valuable information can be gathered before the crop is planted (Asher et al. 2002, p. 19), rather than waiting for plant symptoms to develop.

The ability to measure contaminants is also required to diagnose trace element or metal toxicities. This is especially important in areas impacted by urban and mining activity.

Table 5.6 provides a generalized description of common soil methodologies by analyte. More detail can be found in the Further Reading section.

Method Notes

There will be much debate among soil scientists regarding the "best" methods for measuring the parameters discussed in the chapter. When considering the best methods, readers should keep in mind the following factors:

1. Cost and simplicity: The cost of labour vs cost of capital equipment is a primary consideration when choosing methods.
2. Available instrumentation: This will vary greatly both nationally and regionally. The most powerful and expense equipment available does not necessarily make for good science. Valuable diagnosis can be done with quite simple equipment. For example, a pH and EC meter, and a manual spectrophotometer employing colorimetric methods can be used to measure all of the analytes in Table 5.5 except perhaps Na and K. Na and K can be measured using a low cost flame photometer running on butane gas as used in medical pathology labs.
3. Accuracy and precision requirements are generally lower in commercial science than in research. Accuracy costs money and most high volume North American labs, for example, now use "scooping" a volume of soil rather than weighing,

Table 5.6 Soil methodologies by element

Analyte and units	Basis of the method	Examples and issues
pH in water (pH units)	Indicators or pH probes are used to measure the acid/base activity of the diluted external soil solution	Ratios used are 1:2, 1:5 and 1:10
pH in Ca, Ba or K (pH units)	The presence of an ion displaces the exchangeable acidity and aluminium resulting in a drop in pH compared to water. An indicator of exchangeable acidity	Ratios used are 1:2, 1:5 and 1:10
EC (dS/m, mS/cm, uS/m)	Usually done on the pH in water extract. A measure of the salinity of the diluted soil solution. Must be corrected to provide the true indication of soil salinity by multiplying by a texture factor	Ratios used are 1:2, 1:5 and 1:10
ECEC (meq, cmol+)	The sum of the exchangeable cations. Includes Na, K, Ca, Mg and Al if pH is <5.2 Buffer pH used to calculate exchangeable H^+ and lime requirements	Most commercial methods are actually a sum of exchangeable cations not direct measurements of CEC
N (%, mg/kg)	Extraction of NO_3 using water, NH_4 using desorption agents. Incubation studies used to predict mineralization/demineralization	Difficult to accurately predict soil supply (mineralization rate)
P (mg/kg)	Various desorption agents like acid fluoride or carbonates. Also used are “buffer index” methods to predict sorption/fixation	Highly regionally specific field trial correlations are common
S (mg/kg)	Desorbing anions such as phosphates and chlorides	Mineralization rates of S, like N are difficult to predict
Trace metals Fe, Mn, Zn, Cu (mg/kg)	Use of chelating agents such as DTPA, EDTA	Field trial correlations are needed in all but the most obvious deficiency or excess
B and Mo (mg/kg)	Hot $CaCl_2$ soluble B and Mo is the most common	Reasonably well calibrated

which is faster while still providing sufficient accuracy and precision for diagnostic and monitoring purposes. Where labour is cheaper, accurate weighing is not so disadvantageous.

4. Support infrastructure and ruggedness: Modern instrumentation requires a very considerable industrial support infrastructure, purified gases (argon, helium, hydrogen and nitrogen, for example), service and repair backup and availability of chemicals and standards. Purchase more simple and rugged equipment such as Flame AAS (Atomic Absorption Spectroscopy) if such infrastructure is lacking and develop inter-laboratory relationships to get the more sophisticated analysis done externally by labs that can support this infrastructure.
5. Crop or vegetation type: Many soil tests were developed using field trials and calibrated against crop responses to fertilizers in particular soil types. If these are relevant in your location use them by preference.

Table 5.7 Common plant tissue tests

Analyte and units	Basis of the method	Examples and issues
Total N	Kjeldahl digestion or dry combustion furnace	Leco N analyzer
Nitrate and chloride	Water or weak acid extract, electrometric or colorimetric finish. See Miller (1998)	
Other metallic and non-metallic elements (Ca, Mg, P, K, Na, S, Fe, Zn, Cu, Mn, B, Mo)	Ashing followed by acid dissolution or oxidizing acid, peroxide digestion. ICP and colorimetric finish	Wet chemistry, oxidizing acid (HNO_3 followed by H_2O_2) now most common

6. Soil type: Again, many tests were developed for particular soil types and calibration data may not be as relevant on other soil types (Asher et al. 2002, p. 19; Cook and Bramley 2000, p. 1545). In particular, methods developed for acidic soil (e.g. the Mehlich 3 acid extract) are of dubious applicability to alkaline soils, producing anomalously high Ca, P and trace metal results. Some background research on the origins and applicability of the test is important.
7. Previous experience with a particular method is often the major driving factor for particular researchers or practitioners. This is understandable and is acceptable as long as it does not verge on prejudice against methods that may in fact be more suitable. Workers should always keep an open mind to alternatives outside of their experience and comfort zone.

5.4.2.2 Plant Tissue Analysis

Plant tissue is often analysed by an acid digest method, determining the total amount of an element in a sample. Wet digestion is more common, using a combination of oxidants and acids such as HNO_3, H_2SO_4, H_2O_2 and $HClO_4$ (Sturgeon 2000; Wheal et al. 2011) Table 5.7 presents common plant tissue analysis methods.

To prevent wildly varying results, plant tissue samples must be cleaned and homogenized thoroughly before analysis as even a small amount of soil in a sample can alter the results (Sturgeon 2000). Additionally, the plant species, part, age of the tissue and time sampled are variables that affect the composition (Mills and Bryson 2015), hence careful sampling and documentation is required. Refer to Benton Jones (1998) where recommended plant sampling processes and frequency are outlined for various crops.

5.5 A Step-by-Step Approach

When examining a production system for the first time it is useful to take a systematic step-wise approach to define the limitations within the system and identify the most profitable areas for improvement. By eliminating the most limiting plant growth factors, significant productivity improvements can be made with less expense.

5.5.1 Step 1. What Is the Most Limiting Soil Factor?

5.5.1.1 Physical Problems

Careful profile examination and field tests such as texture, structure and Emerson aggregate tests, together with observations on rooting depth, are an essential first step to identify whether rooting depth will be limited by soil physical factors. Poor rooting depth due to hard pans, hostile dispersive subsoil or high density limits plant access to water and nutrients and often expresses itself as low yield, poor drought tolerance and nutrient deficiency. Crusting due to low organic matter and sodicity leads to poor crop establishment.

Field and laboratory analytical methods for bulk density, permeability and other important physical parameters can be used to add greater certainty to diagnosis (see Klute 1986).

5.5.1.2 Chemical Problems

Acidity (with its associated Al toxicity), sodicity, low exchangeable Ca leading to poor physical properties, alkalinity and salinity must all be identified using the standard range of laboratory testing, pH, EC and cation exchange ratios. The need for ameliorants such as lime, gypsum and acidifying agents can be identified. These are not thought of as fertilizers but do supply nutrients. More importantly they help optimize soil conditions for the uptake of other nutrients.

5.5.1.3 Nutritional Problems

Nutritional deficiencies and toxicities are best determined through soil and plant analysis, before symptoms are visually evident. When plants operate on the law of the minimum, the one element that is deficient will affect plant development regardless of how abundant the other nutrients are. For example, if Mg is deficient, N responses will be depressed. Smith and Loneragan (1997) discuss critical nutrient concentrations that form the basis of most methods of assessing plant nutrient status via plant analysis.

5.5.1.4 Geological Conditions

Sometimes regional deficiencies of certain elements are known of and originate from the inherited geology. A noticeably low level of any particular element would prompt further inquiry, for example, plant tissue analysis. In some areas elevated levels of toxic elements such as As are related to regional geological factors and should not be ignored.

5.5.1.5 Soil Analysis

The standard type of soil analysis for plant available nutrients as well as the basic pH, EC and exchangeable cation rations is the normal line of enquiry. If the methods used are not well calibrated to the particular soil and crop being investigated the results must be interpreted cautiously, but should lead to a “hit list” of those elements appearing most limiting, i.e. can be used to narrow the field of enquiry.

5.5.2 Step 2. Plant Analysis

Once all the soil test data are complete they should then be calibrated using plant tissue analysis. In the simplest case, low levels of an element in the soil may be accompanied by low levels in the plant. This is not always the case; however, no cropping system should be allowed to decline to the point of showing clinical foliar symptoms. Foliar symptoms can occur in the early stages of investigation while adapting the management of soils and nutrients to the needs of plants.

Notionally we establish "normal" ranges for the levels of elements seen in various plants, usually in the mature foliage. Due to complexities of interpretation, some experience is required to use plant analysis to greatest effect. There is a vast literature on "normal" plant tissue levels and interpretation of data. Examples are Benton Jones and Wolf (1996), Srivastava and Gupta (1996), Reuter and Robinson (1997), Weir and Cresswell (1993a, b, 1995, 1997). Some of the difficulties of interpreting such data are discussed as follows.

5.5.2.1 Notes on Using Plant Analysis

There is some difference of opinion on the use of foliage analysis in managing nutrition and soil chemical properties (Wilson and Maguire 2009). In one view, testing soils is analogous to a doctor testing someone's food intake to determine their health rather than taking blood and urine samples, which are analogous to tissue testing of plants. This analogy should not perhaps be taken too far as humans have much better homeostatic mechanisms than plants (Smith and Loneragan 1997) and we are not yet progressed to the point where testing plant sap for electrolyte balance, hormones and sugar levels, for example, have a sufficient research base to be helpful diagnostically in all except the crudest approaches.

In another view it is our experience that soil and plant tissue analysis works best when used together. Soil testing can be a rather crude method of estimating the probability of plant response, but when used in conjunction with a foliar test can be used to quite accurately confirm the existence and reasons for a particular nutritional pathology.

Our view may be expressed as follows:

1. Plants have a moderately well-evolved homeostatic mechanism which means their tissues cannot operate outside of certain ranges of the plant essential elements and thus show clinical symptoms (usually on the foliage) when elements fall below or above extreme ranges.
2. Some of the ranges, even for well-characterized species, are fairly large and moderate deviations from the mean or modal distribution do not support a conclusion of deficiency and response. This is further complicated by factors such as the age of the foliage and time of year. Be wary of narrow ranges, as manganese, for example, is a highly variable micronutrient where leaf tissue buffers fluctuations in root uptake of manganese (Marschner 2012).
3. A notional "normal range" must be established for the species and type of foliage being analysed. This may be, say, two standard deviations each side of the

mean although precise ranges can only be established by experience or exhaustive trials. Despite this, even analysis of plants for which there is no established "normal range" is useful as an overview at the initial Step 1 investigation stage as a screening for gross abnormalities or unusual levels. For example, a seemingly excessive tissue Mn level may not be causing obvious symptoms but may support field observations of waterlogging and low soil pH as a limiting factor causing stress on the plant.

4. The lower a nutrient falls below the notional "normal range" the higher is the probability this is limiting plant growth and that there will be a positive yield response to applied nutrients.
5. At a certain critical level below or above which a nutrient normal range lies the probability of observing clinical symptoms of deficiency or toxicity increases.

This understanding leads to the conclusion, reinforced by practice, that plant tissue analysis is most useful in the following circumstances:

1. To confirm the cause of a clinical symptom. Many extreme symptoms including chlorosis, marginal and interveinal necrosis, xanthophyllic and other discolourations can be diagnosed quite clearly using tissue analysis. Such deficiencies as P, B, Fe, Zn, Mn, Cu, K and Ca lie in this category. Above the critical deficiency level, homeostasis[1] is largely maintained and the only observable effect is reduced growth and yield rather than clinical symptoms. It can be useful, when identifying latent deficiency of "phloem mobile" elements such as potassium to compare old with young foliage, the older foliage showing markedly lower levels as the K is mobilized into the growing new foliage (Paul J. Milham, Adjunct Fellow, Hawkesbury Institute for the Environment and the School of Science and Health, University of Western Sydney, LB 1797, Penrith, New South Wales 2751, Australia, personal communication).
2. N or S deficiency symptoms of general paleness due to low chlorophyll levels is an issue of increasing degree of deficiency rather than a critical level. Here tissue analysis must be interpreted using the "increasing probability of response" model.
3. It is important to confirm visual diagnosis using analysis as many symptoms overlap. Interveinal chlorosis, for example, is typical of both Fe and Mn deficiency as well as P toxicity. Only advisers very experienced with foliar symptoms in particular crops and soil types can reliably identify the deficiency, and even then, may miss multiple deficiency (e.g. of both Fe and Mn) or interaction deficiency (e.g. Fe induced Mn deficiency).

[1] Homeostasis is the maintenance of a steady state. In animals, an example is maintenance of internal body temperature despite swings in external environmental temperature. In the context of plants, homoeostasis refers to a plant's ability to maintain its internal environment (nutrient levels, water content, pH, etc.) within ideal limits in the face of external forces, e.g. nutrient deficiencies or toxicities.

4. Critical stage analysis is where a plant part is tested at some stage prior to harvest to determine if additional nutrients critical to yield or quality are adequate. The most common example would be flag leaf analysis of cereals for N, but leaf petiole analysis of N and P in grape vines at veraison as critical indicators of later fermentation quality is gaining in popularity (Goldspink and Howes 2001).
5. Trend analysis, often associated with understanding responses in trial foliar analysis, should always accompany field trials where confirmation of responses is required. Keep in mind, however, that responses may not be as obvious as expected, since the homeostatic mechanism means a higher yielding plant may show very similar foliar levels to a lower yielding plant because the higher yielding plant takes advantage of the higher nutrient level to grow more thereby diluting the nutrients proportionately in the maintenance of homeostasis. Thus the low yielding plant may show insignificant differences in tissue nutrient levels to the high yielding plant.
6. Calibration of soil testing. A soil test usually provides a probability based conclusion, for example, that Mn looks low compared to the benchmark value. However, soil testing does not provide ironclad prediction of response unless very well-calibrated trials have been used as confirmation. Tissue analysis can improve confidence in results, without the need for field trials. A low level of Mn in the soil, confirmed by a less than normal level of Mn in the foliage, increases the likelihood that a response will be seen with application of the element. Soil testing combined with foliage testing is the most powerful combination to diagnose problems and adapt management accordingly.

Keep in mind that other factors can interfere with nutrient diagnosis, the most common example being pathology, particularly root disease, where deficiency can occur despite healthy level of elements in the soil. Deficiency amid apparent plenty in the soil test should always prompt an enquiry into possible pathology.

5.5.2.2 What Tissue Should Be Tested?

The answer to this question is that it depends upon the purpose of the exercise. The common types of tissue tested and the elements and reasons for testing are summarized in Table 5.8. The reader is also pointed to the detailed discussions on plant tissue testing and interpretation in the Further Reading section.

5.5.3 Step 3. Benchmarking

Once the main soil limitations to crop yield have been assessed and plant tissue analysis conducted, a conceptual model of the "ideal" soil properties for this soil type and crop system will emerge. This type of benchmarking is where a set of prescriptive or ideal soil parameters are established for a given crop, agricultural ecosystem or rehabilitation projection on a given soil type.

The research literature is a good place to commence building a picture of what the "ideal" soil parameters might be. This allows preliminary advice to be

Table 5.8 Common plant tissue tests

Reason for testing	Tissue typically sampled	Elements commonly analysed
Critical yield and protein point	Flag leaves of cereals at ear filling	N
Critical yield and post-harvest quality point	Sap of tomato, curcurbits, prior to ripening	NO_3, K
Symptom diagnosis	Symptomatic or biased sampling. Opportunistic timing. Old vs young foliage	Ca, K, Mg and trace elements Fe, Mn, Zn, Cu, Mo but also salinity effects (Na, Cl, and B)
General health and fertilizer response trials	Unbiased sampling youngest mature blade samples within plant stage and season	All essential major and minor elements

disseminated to land managers and adapted as a result of feedback and working trials in real-life production cycles (see "Step 4. Calibration Trials" and "Step 5. Routine Monitoring" below).

Benchmarking requires the analysis of the soil, parent material, sometimes total elemental analysis of topsoil and subsoil from intact (or at least little-altered) natural soil systems and a comparison of those properties with a notional or preliminary "target range" of soil properties derived from the literature or from judgment informed by the analysis. The notional benchmark or target range is then tested and refined either by systematic experimental trials or trials within the actual production system.

Benchmarking formalizes the manager's understanding of the most limiting aspects of the production system and how best to achieve the most rapid improvements. We could call this "getting it right". Routine soil and crop monitoring as discussed below is more in the nature of "keeping it right".

Managers are advised to assemble a table of benchmark soil properties they are aiming to achieve in their soil management program. As a starting point such a table would resemble the suggested target range values in Table 5.9. The order of appearance of the parameters used in Table 5.9 is simply for convenience and not all test reports will be set out this way. Using the same format your laboratory presents results in removes much tedious transcription. The table is used to compare with your regular monitoring of soil properties. Use of a computer spreadsheet to monitor trends over time is also very useful and, if you have the skills, use graphical presentation.

5.5.4 Step 4. Calibration

For greatest precision the benchmark values would be calibrated and adjusted using field trials over time. Replicated field trials with annual crops, or tree crops with a longer growing period, are slow and costly. What knowledge is available with regard to the preferences of these crops can often be gleaned from the literature and lack of knowledge should not hold up the establishment of draft target ranges.

Table 5.9 Suggested soil target value ranges

Analyte	Units	Suggested range
pH in water (1:2, 1:5, 1:10)	pH units	Non calcareous 5.5–6.8 Calcareous 7.0–8.5 Note plant tolerance to acidity should be considered
pH in Ca, Ba or K (1:2, 1:5, 1:10)	pH units	Non calcareous 5.2–6.4 Calcareous 6.8–8.2
EC	dS/m	1:2 < 1.0 1:5 < 0.5 1:10 < 0.25 Note plant tolerance to salinity should be considered
Cation exchange properties and balance		
Exchangeable H	% of CEC	<5
Exch. Al	% of CEC	<2% for non Al tolerant species
Exch. Na	% of CEC	<5% ideal
Exch. K	% of CEC	5–15% (lower range in clay soils, upper in sandy soils)
Exch. Ca	% of CEC	60–75% higher in calcareous soils
Exch. Mg	% of CEC	15–25%
CEC	$cmol^+/kg$	1–5 low fertility sandy soils 5–15 sandy loam to loams 15–30 organic loams to clay loams 30–60 high fertility clay loams to loams 60–120 high charge clays
Available nutrients		
Nitrate (NO_3–N)	mg/kg	0–5 very low fertility 5–15 low fertility 15–30 moderate fertility 30–60 high fertility >60 likely excessive for most needs
P	mg/kg	(Acid fluoride extracts) 1–5 low fertility forest and poor rangeland 5–10 high status forest and pasture 10–30 broad-acre cereal and improved pasture, perennial tree crops 30–60 high yielding pasture, cropping and perennial fruit tree crops, broad-acre vegetables 60–100 high yielding horticulture and viticulture >100 excessive in all but the highest yielding horticulture, floriculture
Sulphate (SO_4–S)	mg/kg	20–100 normal—Ca phosphate extract, Mehlich 3 >100 normal in high fertility and saline soils
Fe	mg/kg	>50 deficient 50–200 normal >250

(continued)

Table 5.9 (continued)

Analyte	Units	Suggested range
Mn	mg/kg	<20 deficient, or more common in very silaceous soils 20–100 normal >100 can be indicative of periodic waterlogging
Zn	mg/kg	<10 poor agricultural or bushland soils 10–30 normal 50–100 over-fertilized garden soils >100 urban and/or polluted soils
Cu	mg/kg	<3 poor agricultural or bushland soils 3–10 normal 11–30 over-fertilized garden soils >50 urban and/or polluted soils
B	mg/kg	<1 poor agricultural or bushland soils 1–4 normal >10 over-fertilized garden soils >15 urban and/or polluted soils
Mo	mg/kg	
Organic matter	%	(Walkley Black vs LOI vs Dry combustion)[a] <1% low 1–2% broad-acre cropping 2–5% pasture

[a]Walkley Black is a better method for clayey and/or calcareous soils (Ali and Jenkins 1995), however, Walkley Black is costly, time consuming and uses hazardous chromate (Salehi et al. 2011). The cheaper loss on ignition test shows unacceptable errors at levels much lower than about 5% in our experience but is quite acceptable above that level

Once established, these target or benchmark ranges can be verified and refined over time through trials within the production crop, orchard, vineyard or grove. It is relatively simple, for example, to vary the application of one or more elements across a production field, for example, incorporating a useful calibration trial into a production system.

5.5.4.1 In-Field Trials

In dryland agriculture, rainfall will always be the main determining factor of yield. Benchmarking will determine what other factors are likely to limit yield, and in-crop trials validate these benchmarks. Asher et al. (2002) provide some very practical advice on the conduct of simple field trials that could be adapted to in-production trials. Replicating trials and results is essential to confirm conclusions beyond reasonable doubt, however, in-production trials can accept a lower level of stringency as the purpose is not to publish the data in academic texts, but to improve the production system. It is most powerful in areas with little soil variability. Where variability increases, replication and increasing plot size becomes increasingly important to the significance of the conclusions from a trial.

The more variation a given field shows, the more important trial replication becomes (Asher et al. 2002, p. 78). If, however, a field yields in a highly uniform manner, then data obtained without replication may be used.

Fig. 5.1 Above ground harvestable portion of animal forage and the 1 m^2 frame made from soldered pipe used to define it

Fig. 5.2 Gross yield from 1 m^2 harvests in a trial of above ground harvestable portion of forage in a yield increment trial. Zero fertilizer application on the left to highest rate on the right

Most important in small scale in-field trials is record keeping and obtaining objective data. Careful diaries of the types of treatment, and their location so they can be identified at harvest, are vital to making useful conclusions and calibrations of the benchmarks.

Gathering objective harvest data is also critical. Visual assessment is not sufficient and a harvest, preferably of the commercial portion, is needed. Unless highly sophisticated GPS equipped harvesting equipment is available, it is necessary to assess yield using a meter square yield method where yield is manually cut from several square meter chosen randomly from the trial area (see Figs. 5.1 and 5.2).

Without the use of trials, long experience with harvests can be used as a partial, if less accurate, way to calibrate and adjust the benchmarks. This is greatly complicated by seasonal factors and takes experience over many seasons to decide. For example, that responses to potassium application are diminishing as soil reserves build up through potassium application.

Figure 5.3 illustrates the typical shape of a yield in response to the addition of a given element. If you can establish, for example, that by adding a certain amount of fertilizer you get a virtually linear response illustrated by moving from position A

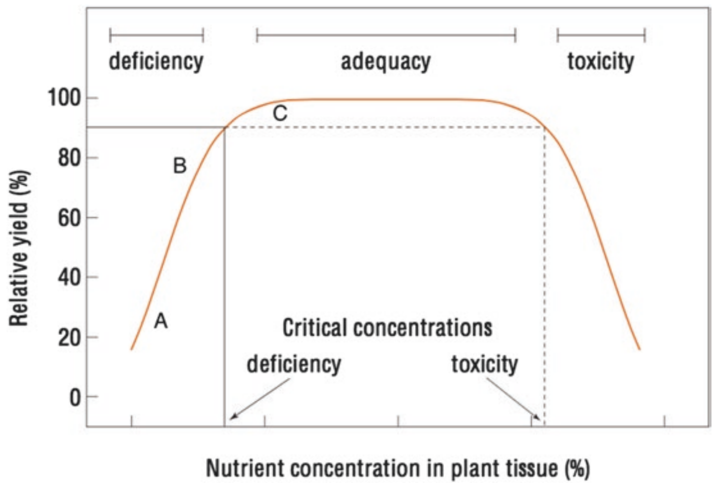

Fig. 5.3 Schematic relationship between relative yield and concentration of a nutrient in plant tissue (Source: Asher et al. 2002, mark-ups by authors of this paper)

to position B on the curve (Fig. 5.3), you can guess that next year you should apply even more fertilizer. If you then establish in the following year that you move from A to B with a linear response but adding twice the amount again does not result in twice the yield (B–C) you can estimate you are approaching the yield "plateau". By correlating these with the soil test results, the benchmarks can be adjusted accordingly.

More effective and useful adaptation of the benchmark values is possible if fertilizer use, yield data, foliar analysis and weather (rainfall and temperature) statistics are also kept from year to year. By plotting these against the trends in soil test values, evidence can be gathered regarding the major determinants of yield, helping to further refine the benchmark values. Wherever possible, areas of chronically poor yield within a crop system should be tested and mapped so that reasons for such special variability can be determined from the testing.

5.5.5 Step 5. Routine Monitoring

Routine monitoring is usually much more narrowly focused than initial benchmarking. In the world's major production systems there are some fairly predictable soil properties and nutrient dynamics that need monitoring. These can be summarized as follows:

1. Soil pH and acidification. In poorly buffered soils (not usually an issue in calcareous soils) employing acidifying production systems (e.g. N fixing crops stimulated by phosphate use) cause the pH and exchangeable base levels to fall, sometimes quite quickly. A simple assessment of pH and pH buffer capacity

every 2 or 3 years, as well as P monitoring is essential to ensure the system remains in control.

2. Nitrogen. The most expensive input to agriculture and the input most likely to result in cost positive yield returns is N, most often as urea. However, the environmental consequences of application of excessive urea can be very serious and many areas in China are suffering severe water pollution as a consequence of indiscriminate application of urea. Monitoring of N is complicated by the dynamics of fixation, mineralization and demineralization, and C/N ratios making it the most difficult element to predict analytically. Despite these difficulties analysis can help avoid damaging application levels of N and monitoring for soil N is discussed below.
3. Phosphorus. P is also a costly import in many developing countries and likely to become more costly. It is often the most pivotal element after N in an agricultural (and ecological) production system and in much broad-acre agriculture is possibly the only element that needs short term (say annual) monitoring to inform nutrient budgets.
4. Potassium. Being the most soluble of all plant nutrients, K is lost most quickly from terrestrial environments especially in tropical soils under high rainfall. Deficiency is highly limiting to horticultural production in particular with its high yields and nutrient removal rates.
5. Trace elements. Usually regionally predictable it is important to monitor response and accumulation of these elements.

Routine analysis shows the following features:

1. It is targeted at limiting elements and soil conditions and does not usually require complete soil chemistry analysis every season.
2. It is used to track changes in the levels or reserves of a limiting element helping prevent costly over-application and yet identify downward trends that need addressing.
3. It is used to recalibrate the target benchmark. It might suggest, for example, that the previous addition of the limiting element resulted in no apparent yield increment suggesting that the adopted benchmark is too high and prompting an adaptation to a lower target value for that element.

Ultimately the purpose of routine monitoring is to identify inputs versus outputs in an ecosystem or agro-ecosystem. Net increase in a nutrient indicates inputs (either from weathering, bioaccumulation or fertilizer use) exceed outputs (removal in harvested portions, runoff and erosion). Such analysis helps pre-empt potential future deficiencies and helps calibrate the benchmark or target values being used to manage the system.

Plant tissue monitoring can be used in such input versus output calibrations to provide a measure of the nutrient losses in the harvested portions, but given the expense, these are probably predictable from the literature anyway. Homeostasis means that crop plant tissue analysis, if the crop is asymptomatic, is much the same from year to year with only slow upward or downward changes. It can be used to most effect in the following circumstances:

1. To minimize N inputs, relatively low levels can be applied as a pre-dressing and then the crop monitored for tissue N at critical stages. For example, flag leaf analysis of cereals can be performed at ear filling to predict the need for additional N to maintain yield and protein content. Exactly calibrated and minimal amounts (as low as 10 kg urea/ha) can then be applied as a foliar liquid application to absolutely maximize use efficiency and minimize environmental losses. The same can be done for some perennial crops, e.g. vines, see Goldspink and Howes (2001). This is very useful to minimize fertilizer costs and losses to the environment.
2. Where particular trace elements are limiting and large fixation losses can be anticipated where the element is applied to soil (for example, metal additions to alkaline soils), critical stage analysis can also be very helpful to inform the application of foliar elemental treatments that are far more efficient than soil application.
3. Where trace elements necessary for animal nutrition are limiting, these can be analysed in the finished grain of forage crop and supplemented in the animals' diet by other means. This is far more efficient than adding these to the soil or growing crop. Notable elements in this category are I, Se and Co.

5.6 Other Issues

5.6.1 Pollution, Contamination and Toxicity

Due to the strong exclusion mechanisms occurring right up the soil, plant and animal food chain, instances of toxicity in humans and animals from ingestion of contaminated plant food are remarkably rare. Where they do occur, it is usually in cases of industrial contamination or from acid mining waste. Regionally elevated levels of such elements can occur. Laboratory analysis using an oxidizing acid digest, e.g. Rayment and Lyons (2011) Chap. 17 is used to confirm suspicions of mining or industrial activity.

5.6.2 Environmental Rehabilitation

It is often useful to analyse healthy and preferably natural unaltered soils from ecosystems that are intact or only partially altered within the same geology and soil/vegetation landscape to compare with the agricultural, mining or urbanized soils that are the subject of study.

Conventional empirical "availability" testing can be useful in this context but the use of total elemental levels of the important essential plant elements can also be highly instructive.

Such analysis of the topsoil as well as deeper subsoil and parent material layers provides information on a range of properties:

- The relative development and "intactness" of the A horizon
- The degree of erosion or degradation of the topsoil relative to the intact profile
- Changes in topsoil organic matter content as a result of farming or other human activity
- The degree of natural bioaccumulation of limiting plant nutrients
- The most limiting plant nutrient elements in the ecosystem
- The quantity and type of plant nutrient input (fertilizer) most likely to result in the greatest yield increment or improvement in ecosystem function.

This analysis can then be used to plan a nutrient improvement program, concentrating on those elements that will be slowest to bioaccumulate under even good soil husbandry practices or natural rehabilitation. For example, K is often rapidly lost from soil ecosystems in high rainfall environments and rapidly becomes a limiting element when the natural forest cycling is disturbed by permanent clearing. This will usually be seen easily in a soil test comparison as reduced exchangeable or extractable potassium.

This kind of comparison is particularly useful in land rehabilitation such as after mine closure both for returning the land to natural vegetation or for conversion to agriculture. A set of benchmark nutrient levels can be established and a fertilizer and soil improvement program, for example, incorporating leguminous cover crops to build soil N, can be established targeting the most limiting elements for enhancement with fertilizer.

Total elemental analysis is also useful to pre-warn soil managers of likely problems, not just with plant nutrient but also with animal husbandry. Such trace element deficiencies are often related to geological distribution and can be identified at the regional level.

As with cropping, monitoring of plant tissue can provide additional useful information in environmental rehabilitation. Both very extreme, usually symptomatic clinical deficiency and depressed growth as the result of mild deficiency can be identified early and corrected.

One difficulty is that, while "normal range" data is widely available for crop and forage and even forestry plants, much less such data is available for species used for environmental rehabilitation purposes. The land manager will be left with the task of gathering background benchmark analysis for the species they are using in their particular program. This analysis can certainly be done during a program of initial benchmarking of an ecosystem as recommended in Step 3 and is a most useful exercise.

1. Always sample the same time of year, preferably late growing season
2. Always sample within species and variety.
3. Always sample the same foliage, generally targeted symptomatic foliage if you are chasing symptoms and "youngest mature blade" if you are benchmarking.

4. Some replication within and between years provides a better basis for developing benchmark or target ranges.
5. Benchmark comparisons should be from plants growing in similar environments. Comparisons of field grown material with nursery grown stock where nutrient levels are optimized are of reduced value.

Foliage analysis is certainly useful where comparative soil treatments are used in rehabilitation, to help rationalize results and calibrate both benchmark target ranges and inform future trials.

5.7 Conclusion

Laboratory analysis of soil and plant tissues is critical for successful management of production systems. Analysis allows the soil manager to take pre-emptive rather than reactionary approach: addressing chemical and physical imbalances before they occur, and adapting management practices accordingly.

Continued and regular analysis also provides benchmarks of ideal or limiting parameters. These can be calibrated through trials, site knowledge and experience.

Both plant and soil analysis are essential to fully understanding adaptive soil management. In the developing world, these processes will help farmers implement tailored fertilizer practices. However, soil and plant analysis involve costs, and small scale farmers are unlikely to be able to afford the fees, despite the potential offset in fertilizer costs. As such, public subsidies and support may be essential (Ryan 2000, p. 2151) at least during the initial stages of development of a functioning agricultural laboratory infrastructure.

Large government subsidized laboratories with the advantage of scale would be another approach.

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Microbial Proteins and Soil Carbon Sequestration

6

Geeta Singh, Seema Sangwan, Ekta Narwal, and K. Annapurna

Abstract

Soil microorganisms catalyze various ecological processes such as nutrient cycling. Microorganisms produce as well as consume greenhouse gases, including CO_2. There is a growing interest world wide in sequestering atmospheric C and improving soil properties. Mycorrhizal fungi form a mutualistic association with plants receiving photosynthate from plants. The production of a glycoprotein glomalin by hyphae of AMF is directly linked to soil aggregation and positively correlated with soil aggregate stability. It has been observed that AMF hyphal abundance and soil aggregation are also positively correlated with C and N sequestration. Small (~100 amino acids) cysteine-rich proteins called hydrophobins are expressed only by filamentous saprophytic fungi belonging to ascomycetes and basidiomycetes. Another group of proteins called chaplins are produced by streptomycetes which have shown promise for the carbon sequestration in soils.

Keywords

Carbon sequestration • Glomalin • AMF • Chaplin • Soil organic carbon (SOC)

6.1 Introduction

Terrestrial carbon sequestration is an important step towards mitigating anthropogenic CO_2 emissions. The estimated increase in atmospheric CO_2 levels at a rate of 0.4% per year has been predicted to double by 2100 mainly due to human actions

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and their interference, e.g., land use changes and combustion of fossil fuels (IPCC 2007; Lal 2011). Increased CO_2 concentrations in the atmosphere are thought to be partly contributed by the soil under agriculture. According to an estimate soils have contributed 55–878 billion tons (GT) of carbon to the total atmospheric CO_2 (Kimble et al. 2002). Considering the fact that globally over one third of arable land is under agriculture (World Bank 2015), therefore, finding ways to increase soil carbon in agricultural systems will be a major step towards using soils as a sink. Sequestration of C entails the channelizing of atmospheric CO_2 into long lived pools to mitigate or deter their immediate remittance.

Soil which acts as a carbon store house is of great significance in global carbon cycle. The soil carbon comprised of the organic and inorganic carbon fractions, and estimated to be approximately over 2250 GT in the top 1 m depth (Batjes 1996). Soil carbon plays important roles in maintaining soil nutrients, structure, and tilth (Bronick and Lal 2005), improving soil water retention, filters pollutants, fostering healthy soil microbial communities (Wilson et al. 2009), and providing fertility for crops (Schmidt et al. 2011). Overall it enhances soil productivity and quality, besides provision of environmental benefits. The critical limit of SOC concentration for most soils of the tropics is 1.1% but average availability is relatively low (0.1–0.2%). Therefore, increasing SOC concentration from 0.1 to 0.2% to a critical level of 1.1% is a major challenge for tropical ecosystems. Further, under tropical ecosystems, agricultural soil shows 75% higher depletion of organic carbon in comparison to their uncultivated counterparts. The depletion is accelerated when the output of C exceeds the input and under severe soil degradation conditions. The capacity to store carbon is highest for tropical soils but the rate of sequestration is low. Soil respiration plays a pivotal role in this process as large amounts of CO_2 and CH_4 emissions originate from these processes. Soil carbon sequestration transfers atmospheric carbon into the soil by mediation of plant photosynthesis and keeping susceptible soil-based carbon pools protected from microbial activity that will otherwise release the carbon back to the air. Enhanced soil organic carbon (SOC) and soil inorganic carbon (SOI) stocks are required through wise land usage and RMPs. Common RMPs that accelerate the microbial mediated SOC sequestration are mulch farming, conservation tillage, agro-forestry, and diverse cropping systems, cover crops or periodic green fallows, and integrated nutrient management, including the use of manure, compost, bio-solids, improved grazing, and forest management (McDaniel et al. 2014; Tiemann et al. 2015).

6.2 Dynamics of Soil Organic Carbon

Soil microbial population is of great significance in cycling of carbon in soils. Their activity in turn is regulated by temperature, moisture, texture and structure, tillage, and cropping management, all exert interactive cumulative impacts on carbon dynamics. External C sources added to soil as crop residues undergo microbial decomposition resulting in loss of 2/3 of the carbon. A fraction of it is assimilated as the microbial biomass and a major part of it is released into the atmosphere as

CO_2. The process results in accumulation of relatively resistant SOC fraction which is partially transformed and may be attacked later by the microbial population. Measurements with ^{14}C dating technique revealed an average age of soil organic carbon to be more than 1000 years (Schmidt et al. 2011).

In soils carbon and nitrogen turnover are interlinked and these are being driven by microbial biomass. Carbon to nitrogen ratios (C:N) of crop residues/organic matter in the soil regulates the soil processes. The average C:N ratio of stable form of SOC, the humus, and soil microbial biomass are approximately 10–12, 10, and 7, respectively (Juma and McGill 1986). Carbon and nutrient elements in the microbial biomass are continuously recycled in the soil and contribute to long lasting continual variations in soil organic C. The total organic carbon in soil at any given time is the net outcome of turnover of microbial biomass, rate of respiration, nitrogen and phosphorus mineralization. All these processes are tightly linked with the microbial metabolisms in soil. The accumulation C in agricultural soils is governed by a harmonious equilibrium between plant productivity and heterotrophic respiration through SOM decomposition. Under elevated CO_2 improved plant growth causes an increase in photosynthetic C input to soils, which in turn triggers or quickens the growth of microbes. This leads to the N demand thereby limiting the availability of soil N and its uptake by the plant under elevated CO_2 (eCO_2). On the other hand, positive feedbacks of soil microbial communities under eCO_2 may accelerate SOM decomposition and potentially result in soil net C losses. Increased microbial respiration occurs when plants are incubated with elevated CO_2 not only due to increased belowground carbon allocation but also as a result of specific interactions between plants, rhizosphere bacteria, and mycorrhizal fungi (MF). Meta-analysis of soil respiration studies undertaken in non-agricultural ecosystems spanning over nearly five decades revealed a temporal increase in global soil respiration of 0.1 Pg C $year^{-1}$ from 1989 to 2008 corresponding to a Q10 of 1.5. These results suggested an acceleration of the terrestrial carbon cycle and the impacts of warming on respiration and sequestration (Bond-Lamberty and Thomson 2010). Another study to support these observations was undertaken by Mahecha et al. (2010) who synthesized ecosystem respiration data from 60 diverse sites (habitats) and found an inherent temperature sensitivity of soil respiration. These observations strongly indicate the critical role of soil microbiota in determining the balance of C mineralization and sequestration.

6.3 Mycorrhizal Fungi

Mycorrhizal fungi form a mutualistic association with plants (Philip et al. 2010) where soil nutrients are exchanged for plant-assimilated C. Due to their extensive hyphal mycelia in comparison with saprobic fungi AMF represent nearly a 30% of soil microbial biomass (Rillig et al. 2001). Plants allocate an estimated 10 ± 20% of net photosynthate to mycorrhizal fungi. Mycorrhizal plants transfer 23% more assimilated C belowground compared to non-mycorrhizal plants (Rygiewicz and Anderson 1994) thus altering soil C storage. A number of parameters influence carbon transfer from plants to mycorrhizae and include plant genotype and species (Hoeksema and Classen 2012), season and soil nutrient availability (Olsson et al. 2010). In a study undertaken in three different natural ecosystems, increases in hyphal length, glomalin concentrations, and a change in soil aggregate stability were recorded under elevated CO_2 condition. The copious production of a glycoprotein glomalin, by hyphae of AMF and stimulation of arbuscular mycorrhizal fungi (AMF) by elevated atmospheric carbon dioxide (CO_2) have been assumed to be a major mechanism facilitating soil carbon sequestration by increasing carbon inputs to soil and by protecting organic carbon from decomposition via aggregation. Photosynthates transferred to mycorrhizal fungi can contribute to soil C storage if fungal tissues decompose more slowly than fine roots (Langely et al. 2006) or if their biological residues persist for long period (Clemmensen et al. 2013). The aftermath outcome of elevated CO_2 and associated rising temperature globally could heighten the respiration and mobilization of soil organic matter. For example, temperature affects carbon allocation from plant to fungus and allocation within AMF networks, with a possible increase in respiratory carbon losses in a warmer climate that are not offset by increased AMF growth. Nonetheless, much remains unknown about interactions between temperature and managed soil carbon sequestration (SCS).

6.4 Mycorrhizal Fungi for Aggregate Formation

The stability of the soil aggregates which are the basic sites of the soil C is vital for the SOC sequestration. The presence of stable soil organic C is directly linked to soil aggregation. Flocculation, rearrangement, and cementation of soil particles eventually lead to soil aggregation in which soil organic C, clay, minerals especially biota have crucial and significant importance (Bronick and Lal 2005; Rillig and Mummey 2006). Biotic factors include mainly the plant roots and fungal hyphae that contribute to soil aggregate stabilization. Organic carbon in soil plays an important role in soil aggregation. Among the soil fungi, Arbuscular Mycorrhizal Fungi (AMF) appear to play a predominant effect on aggregates formation because the symbiosis significantly changes the root functioning.

The contribution of AMF to stabilization of aggregates was thought to be through entrapment of soil particles by fungal hyphae, the filamentous structures making up the body of the fungus and its role in aggregate stability (Wright and Upadhyaya 1998) have under elevated CO_2. AMF hyphae can promote formation of soil macroaggregates and reduce SOC decomposition. In a study undertaken in three different natural ecosystems, increases in hyphal length, glomalin concentrations, and a change in soil aggregate stability, was recorded under elevated CO_2 condition. The copious production of a glycoprotein glomalin by hyphae of AMF and stimulation of AMF by elevated atmospheric carbon dioxide CO_2 was found to be a major mechanism facilitating soil carbon sequestration. This is achieved by two ways (a) by increasing carbon inputs to soil and (b) protection of organic carbon from decomposition via aggregation. The AMF aids in the soil aggregation by secretion of the glycoprotein, besides it increases the microbial biomass. Aggregates store and protect additional organic carbon until the aggregates break down. Since glomalin production appears to be directly linked to carbon supplied by plants, production of glomalin may be positively affected by increased atmospheric CO_2. Hyphal length and glomalin content are positively correlated with aggregate stability. Many reports have proved the existing positive correlation between AMF hyphal abundance and soil aggregation and C and N sequestration. Stabilization of aggregates amplifies the role of glomalin in soils because carbonaceous compounds are protected from degradation inside of aggregates. Microaggregate formation substantially limits C decomposition losses. The other indirect benefit of AMF is the protection offered to the plant against various biotic and abiotic stresses that may accompany climate change, thereby improving the plant growth. These multifarious actions of the mutualistic fungi in response to the elevated atmospheric CO_2 levels may contribute to the carbon sequestration. This results in the addition of more crop residues and release of organics as root exudates in the soil which further enrich the soil C content. The current body of work on mycorrhizal dynamics suggests that elevated CO_2 might augment global pools of C in living, dead, and residual mycorrhizal tissue by increasing productivity in different habitats.

6.5 Glomalin

In soil microenvironment AMF produce glomalin (Wright and Upadhyaya 1996), a hydrophobic and recalcitrant glycoprotein. Axenic cultures of AMF showed the presence of glomalin, ~80% in hyphal wall, and only a minor proportion was secreted into the environment (Rillig and Mummey 2006). The average composition of glomalin is C: ~37%, N: ~3–5%, and contain iron (Lovelock et al. 2004). It is present in soils in concentrations that are up to 4 times than that of humic acid concentrations, is persistent and associated with the insoluble humus or mineral fractions after treating soils with sodium hydroxide (Comis 2002). Glomalin is insoluble and possibly hydrophobic in its native state (Rillig 2004a). Due to strong relationship demonstrated between soil aggregate stability and glomalin concentration (Wright and Upadhyaya 1998; Wright and Anderson 2000) researchers proposed that mycorrhizal fungi contribute to enhanced soil organic matter stabilization by increasing soil aggregation (Daynes et al. 2012). Strong experimental evidences indicate that glomalin directly increases micro-aggregate hydrophobicity and stability (Rillig et al. 2010). Treseder and Turner (2007) reported that glomalin production varies among AMF taxa and with growth conditions, land use (disturbance), and plant species compositions.

These observations were further supported in long-term field experiments where a gradient of AMF abundance was created. The results revealed that AMF was strongly positively correlated to soil aggregation and carbon levels (Wilson et al. 2009). Because of its role in soil particle aggregation, glomalin is thought to significantly reduce organic matter degradation by protecting labile compounds within soil aggregates thus enhancing carbon sequestration in soil ecosystems (Rillig

2004b). Additional field studies have indicated that the quantity of soil organic matter derived from mycorrhizal tissue might rise under CO_2 enrichment. Rillig et al. (1999) reported an increase in glomalin concentrations in soil from a chaparral system exposed to elevated CO_2 for 3 years.

Some of the agricultural management practices influence AMF and thereby account for soil carbon sequestration. For instance, in no tillage system (NT) Wright and Anderson (2000) found a significantly higher glomalin concentration than under conventional (CT) management. This was further supported by observations where application of the fungicide Captan (*N*-Trichloromethylthio-4-cyclohexene-1,2-dicarboximide) caused a reduction in the concentrations of soil C and acid hydrolysable carbohydrates in NT soils, but not in CT soils (Hu et al. 1995). This indicated that NT induces a higher fungal (saprophytic and mycorrhizal) biomass, which leads to a quantitative and qualitative improvement of SOM.

However, the increase in saprophytic fungal biomass under NT not only leads to an increase of mineralizable organic matter (MOM), but may also affect the accumulation of plant-derived C (i.e., particulate organic matter [POM]). Six et al. (1998, 2000) reported increased macro-aggregate turnover in conventionally tilled soil causing a loss of POM and MOM. Soil fungi retard macro-aggregate turnover due to their positive influence on aggregate stabilization. Mycorrhizal fungi can also slow decomposition by monopolizing humus layers and reducing activity and abundance of free-living decomposers (Lindahl et al. 2010; Orwin et al. 2011). A better understanding of glomalin, hydrophobins, and chaplins would directly lead to new or modified management practices for agro-ecosystems and other managed systems.

6.6 Hydrophobins, Chaplins, and Microaggregates

Manipulation of plant–fungal interactions could lead to further gains in C sequestration. In soil environment a ubiquitous class of fungal proteins hydrophobins are produced. The name hydrophobin was originally used due to their high content of hydrophobic amino acids (Armenante 2008). The proteins are secreted by fungi into liquid media or remain at the surface of aerial mycelia (Stubner et al. 2010). Hydrophobins appear much more widespread in their distribution among fungi, occurring in numerous basidiomycetes and ascomycetes (Linder, 2009). Hydrophobins play important roles in mycelia formation, but they also alter the hydrophobicity of spores, other cell surfaces, and presumably various biological surfaces (Gebbink et al. 2005). Hydrophobins are a group of small (~100 amino acids) cysteine-rich proteins that are expressed only by filamentous saprophytic fungi belonging to ascomycetes and basidiomycetes. After their discovery and separation from *Schizophyllum commune* in 1991 (Wessels et al. 1991), chemical characterization showed it to be of two categories: class I and class II. Hydrophobins can self-assemble into a monolayer on hydrophobic:hydrophilic interfaces such as a water:air interface. The monolayer formed by class I hydrophobins has a highly ordered structure, and can only be dissociated by concentrated trifluoroacetate or formic acid. Monolayer assembly involves large structural rearrangements with respect to the monomer. These proteins are highly hydrophobic in nature and improve water stability of soil aggregates (Piccolo and Mbagwu, 1999), thus favoring carbon storage in soil micro-aggregate (Spaccini et al. 2002).

Climate change and associated environmental and edaphic conditions are known to elicit important responses in fungi, and their proteins hydrophobins (Rillig et al. 2002). For example, aggregates formed by the hydrophobin SC3 (from *Schizophyllum commune*) could not be dissolved in detergents (like SDS) or most solvents, except strong acids, e.g., trifluoroacetic acid (Wösten 2001). Thus similar to glomalin, hydrophobins concentration also has a positive correlation with water stability of soil aggregates (Wright and Upadhyaya 1998; Rillig 2004a, b).

Another class of proteins, analogous to the effects of hydrophobins are chaplins produced exclusively by gram positive bacterial domain streptomycetes (phylum Actinobacteria) these confer hydrophobic properties to surfaces, but details of chaplin interactions with organic matter and micro-aggregates are not well understood (Gebbink et al. 2005). There is need to identify specific sources of chaplins and to understand their functions and dynamics. Also, it is required to determine the potential roles and mechanisms of hydrophobins in microaggregate formation and to assess their dynamics and management potential in situ. Using molecular ecological approaches assays of glomalin, hydrophobin, and chaplin functional genes will be required for assessment of management strategies. In this direction, gene sequences for proteins responsible for the promotion of sequestration have been identified (Purin and Rillig 2007, 2008) and can be used for PCR primer development targeting soils. In addition to mitigating carbon emissions, increasing soil carbon can have profound effects on soil quality and agro-ecosystem productivity. Crucial research gaps include the responses of micro-aggregate formation and destabilization to changes in soil microbial community as influenced by both rising temperature and increasingly variable climate regimes.

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Part II

Adaptive Soil Management Strategies

Use of Soil Amendments in an Integrated Framework for Adaptive Resource Management in Agriculture and Forestry

7

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Abstract

Agricultural practices involving intensive applications of chemical fertilizers can be harmful to the environment. Soil amendments can serve as an alternative source of plant nutrients and simultaneously improve the physical, chemical and biological properties of soils. Many soil amendments are produced from organic and inorganic waste materials. The amendment application practices therefore not only support the agricultural productivity but also facilitate an environmental friendly disposal and recycling of the wastes. This also helps the farmers to reduce their cost of production. Most of the soil amendments supply nutrients to plants over a longer period of time in a slow release process. However, best management practices should be adapted in order to harness the optimum benefits of soil amendments in agricultural and forestry production systems. This chapter

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aims to present an overview of various soil amendments in relation to their already existing and/or potential applications for improving the productivity and health of soils.

Keywords
Fertilizer • Soil amendment • Soil health • Nutrient management • Crop productivity • Waste recycling

7.1 Introduction

Materials (other than those used primarily as fertilizers) that are worked into the soil or applied on the surface to enhance plant growth are generally known as soil amendments (S347 Glossary of Soil Terms Committee 1997). Soil amendments are used for improving the physical properties of soils such as soil structure, water permeability, infiltration, retention, drainage, aeration, and temperature, and also for optimizing soil reaction and nutrient supplying capacity. The aim of amendment application may vary from soil to soil. For example, amendments are applied in a light textured soil in order to improve the water holding capacity, whereas the intention in a clayey soil is to improve the water infiltration. The sub-set of soil amendments, which measurably improve soil physical conditions by better aggregation of soil particles, thus increases the amount of micropore spaces and facilitates air exchange, water movement, and root growth, are also known as soil conditioners (S347 Glossary of Soil Terms Committee 1997). While most of the amendments primarily contribute to the improvement of soil physical properties and a better plant root development, they often become beneficial by indirectly supplying numerous essential micro- and macronutrients or changing and maintaining an optimum soil reaction (pH) which is congenial for plant growth.

"Fertilizers" and "soil amendments," both the terms are commonly used for a wide array of materials that are added to soils to have some beneficial effect pertaining to improve plant growth. Their source of origin may be either organic (e.g., bone meal), or inorganic (commercially produced fertilizers, e.g., urea, single super phosphate and muriate of potash). However, many of them serve dual purposes, i.e., both fertilizers and soil amendments.

Agricultural practices involving intensive applications of chemical fertilizers can be harmful to the environment. Soils have a specific storage and supplying capacity of nutrients. While excess nutrients can cause eutrophication, phytotoxicity, and other contamination, strong binding of them to soil colloids may also infer poor plant growth. Soil amendments are known to address these issues in both the scenarios (Rechcigl 1995). They can also play the most crucial role in the revegetation of abandoned or contaminated sites by promoting sustainable forestry development. However, a best management practice should be followed in order to harness the optimum benefits of soil amendments in agricultural and forestry production systems. This chapter aims to present an overview of various amendments in relation to their already existing or potential applications for improving soil productivity and health.

7.2 Classification of Amendments

Soil amendments can be classified either based on their sources or purposes of application (Fig. 7.1). According to their originating resources, amendments can be organic (e.g., manures and composts, sewage sludge and biosolid, biochar, microorganisms, etc. (Fig. 7.2)), inorganic (e.g., lime, gypsum, rock phosphate, pyrite, zeolite, clay minerals, etc.), synthetic (e.g., hydrogels), and industrial byproducts (e.g., fly ash, basic slag, red mud, etc.). Most of these materials may impart improvement in one or multiple physical, chemical or biological attributes of soils, which finally translates into increased soil productivity and health.

7.3 Organic Amendments

Organic amendments are obtained mostly from materials which are of biological or organic origin (Fig. 7.2). Following applications, they play multiple roles in soils—improve soil physical, chemical, and biological properties (Table 7.1). Amending soils with processed biomasses or organic matter also holds well-known influence on carbon sequestration and greenhouse gas emissions (Thangarajan et al. 2013).

7.3.1 Manures and Composts

The concept of organic farming and biodynamic agriculture started with the use of organic manures to supplement plant nutrients over a longer period of time. In many parts of the world, long-term fertility experiments (LTFE) included the component of manure to study the role of organic fertilizers for a sustainable agriculture. Manure used in agriculture generally comes from sources like cattle dung, sheep/goat dung, poultry excreta, etc. (Fig. 7.2). Average, well-decomposed farmyard manure (FYM) contains 0.5–1.0% N, 0.15–0.20% P_2O_5, and 0.5–0.6% K_2O. The ideal C:N ratio in FYM is 15–20:1. Apart from NPK, manure also contains several

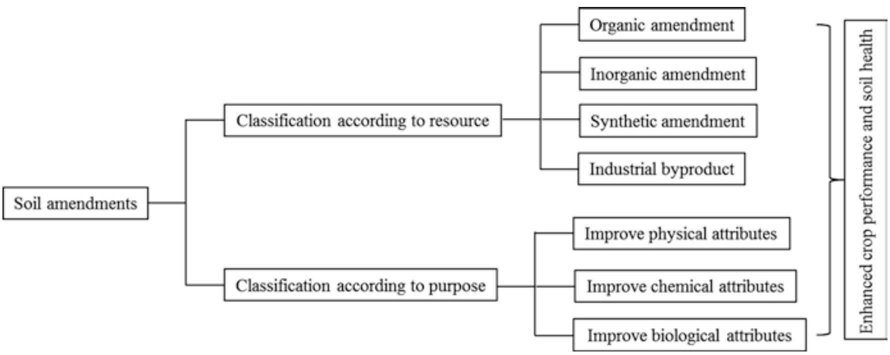

Fig. 7.1 Classification of soil amendments

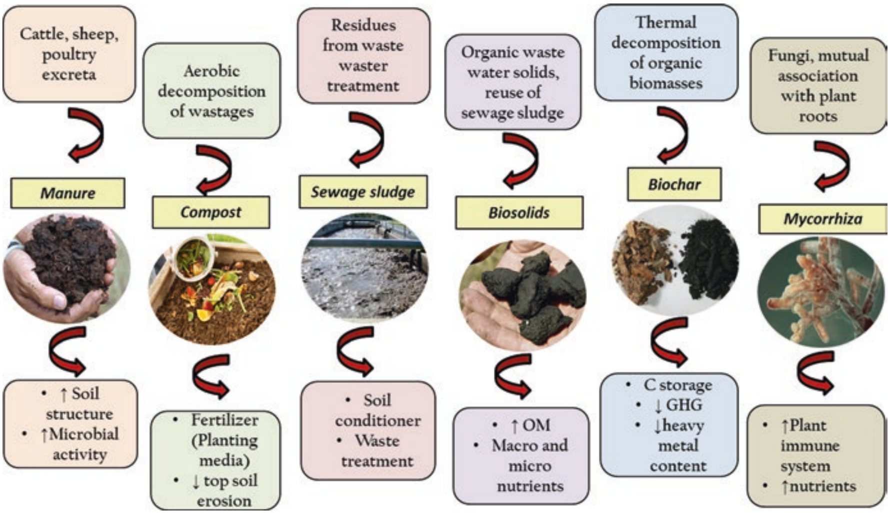

Fig. 7.2 Schematic diagram showing commonly used organic amendments, their sources, and potential agricultural uses

Table 7.1 Organic soil amendments and their uses

Organic amendment	Beneficial effects
Sewage sludge	Organic nutrient source Soil conditioner Waste recycling
Biosolid	Nutrient rich organic matter Improve and maintain soil productivity Improve plant growth Supply macro- and micronutrients
Biochar	Sequester C in soil Reduce greenhouse gas emission (NH_3, N_2O, and NO) Reduce nutrient leaching Improve soil physical (soil structure, texture, surface area water holding capacity, etc.), chemical (pH, CEC, surface functional groups, etc.), and biological (microbial growth) properties Remediate heavy metals
Manure	Supply nutrients Improve soil structure Enhance microbial activity and promote element mineralization
Compost	Supply humus, nutrients, and organic matter, promote soil bacteria Control topsoil erosion Good planting media in wetlands
Mycorrhiza	Tolerate drought condition Improve nutrient use efficiency Improve plant immune system

micronutrients like Fe, Mn, Mo, B, and Co. The long-term addition of manures can result in stable pool of C (Verma and Sharma 2007; Wang et al. 2007), N (Kelln et al. 2012), P (Kelln et al. 2012), and micronutrients (Sukkariyah et al. 2005), which enhances the quality of soil as a whole.

The organic manure which is obtained through the aerobic, anaerobic, or partially aerobic decomposition of various biomasses including crop, animal, human, and industrial wastes is generally called the compost. The term is derived from the Latin word *componere* which means "mixing." The composts consist of three classes: rural compost (0.5% N, 0.2% P_2O_5, and 0.5% K_2O), urban compost (1.5–2.0% N, 1.0% P_2O_5, and 1.5% K_2O), and vermicompost (0.6% N, 1.5% P_2O_5, and 0.4% K_2O). Apart from adding raw organic matter to soil, composts have many other beneficial roles including reduction of nutrient losses (Kelln et al. 2012), enhancing abundance and diversity of beneficial soil fauna like earthworms (Mbau et al. 2015), increasing the amounts of micronutrients (Li et al. 2007), etc. (Table 7.1).

7.3.2 Sewage Sludge and Biosolid

Sewage sludge is termed as the residue which is produced at the end of wastewater treatment processes. Typically, the liquid and solid parts of the wastewater are separated through a combination of physical, chemical, and biological treatments. Following discharging the liquid part into the aqueous environments, the solid part can be removed and used as fertilizers with or without further treatments (Fytili and Zabaniotou 2008). Sewage sludge has a wide range of applications not only as a waste management practice, but also as an organic soil amendment and soil conditioner (Yoshida et al. 2015).

The organic solid obtained at the end of wastewater treatment process is known as biosolid. This is a kind of reuse of sewage sludge. To produce biosolid, sewage sludge is first dewatered and then treated to a standard quality that has potential for agricultural uses (Pawlett et al. 2015). Biosolids are generally used as a soil amendment because of their high organic matter contents. They can supply nutrients for plant growth and development (Fytili and Zabaniotou 2008) (Table 7.1).

7.3.3 Biochar

Biochar is produced as a by-product of oxygen-restricted thermal decomposition of various organic biomasses at variable temperatures (Clough et al. 2013). There have been increasing interests on biochar because of its various beneficial applications (Knowles et al. 2011). Biochar can (a) act as a potential C sequester in soil (Li et al. 2015), (b) reduce nitrogen (N) loss (Singh et al. 2010; Mandal et al. 2016a), (c) improve nutrient retention capacity (Case et al. 2012), (d) remediate contaminated soils and waters (Ahmad et al. 2014; Mandal et al. 2017), and (e) improve soil physical, chemical, and biological properties, and thus improve soil health (Clough and Condron 2010) (Table 7.1). Thus, biochar can act as a soil amendment because of its ability to provide agronomic benefits to plants (Mandal et al. 2016b). It can act as an active supplier of nutrients to the plant roots. Simultaneously, it can supply nutrients to the microorganisms that are involved in the cycling of other nutrients in soils. Therefore, biochar can improve plant growth directly by supplying nutrients from the source within itself, and also indirectly by its ability to adsorb and retain additional nutrients (Mandal et al. 2016b).

7.3.4 Mycorrhiza

The Mycorrhizae group of fungi (also known as Arbuscular Mycorrhiza or AM fungi) is a typical example of mutual association of microorganisms with plant roots. It is found either on the surface or in the inter-cellular spaces of roots. They primarily facilitate the root hairs to reach into the location where nutrients are localized in soils. These superfine, root-like structures of fungi additionally help plant root hairs to absorb P, Zn, and other nutrients. The effects of mycorrhizae in increasing the uptake of water and nutrients by plants are more prominent in relatively unfertile and nutrient-poor soils. By producing hormones and antibiotics, mycorrhizae also help to enhance root growth and provide disease suppression, and also physically protect the nematode attack on roots (De La Peña et al. 2006). However, since the dependency of plant species on AM colonization varies, cereals are less dependent on these microorganisms than legumes (Singh Gahoonia and Nielsen 2004).

7.4 Inorganic Amendments

Inorganic amendments are generally mined materials or man-made. Many inorganic amendments play a key role in altering and maintaining the soil reaction at a level optimum for plant growth. The addition of course-textured inorganic amendments can create additional pore spaces in soils. Many of the amendments following application to soils can improve the nutrient retention capacity in the root zone by enhancing the soil's cation exchange capacity (CEC). Sometimes inorganic amendments also provide plant nutrients which is an additional benefit. Some of the important inorganic amendments and their potential benefits are listed in Table 7.2.

7.4.1 Lime/Limestone

Limestone is a common sedimentary rock which contains predominantly calcite mineral ($CaCO_3$). Limestone contains both calcium (Ca) and magnesium (Mg) and generally applied to soil as an amendment to correct the soil acidity (to increase soil pH) (Sarkar and Naidu 2015). Mostly two types of limestones are available, e.g., dolomite limestone and calcite limestone. The dolomite limestone contains both calcium and magnesium carbonate [$CaMg(CO_3)_2$] almost in equal proportions. It is a source of both Ca and Mg while calcite limestone supplies only Ca. Since Ca

Table 7.2 Important properties and utilizations of some inorganic soil amendments

Amendments	Properties	Utilization
Limestone	Sedimentary rock composed of calcite and aragonite (crystal form of $CaCO_3$)	Reclamation of acid soil
Gypsum	Soft sulfate mineral composed of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$)	Reclamation of sodic soil
Rock phosphate	Non-detrital sedimentary (sometimes igneous) rocks which contain a high amount of minerals having phosphate	Natural slow release P source for plant
Pyrite	Iron and sulfur containing mineral, and generally it has the chemical composition FeS_2	Reclamation of alkali soils besides being a source of plant nutrients like S and Fe
Clay minerals	Weathered aluminosilicate minerals	Improve water holding capacity in water repellent soils
Zeolite	Porous and crystalline naturally occurring aluminosilicate mineral	Increases nutrient and water retention within soil
Waste mica	2:1 silicate mineral, comes under muscovite group having chemical composition of $(OH)_4K_2(Si_6Al_2)Al_4O_{20}$	Natural amendment for highly weathered soil and particularly K nutrition for plant
Diatomite	Silica-based mineral derived from the skeletons of diatoms (microscopic algae)	Effective in increasing aeration porosity and drainage in fine soils
Pumice	Highly porous siliceous volcanic material	Enhance water retention in fine texture soil
Perlite	Porous lightweight siliceous material, chemically inert and resistant to weathering	Increase total porosity and water retention capacity in soil

is more essential and needed in a higher quantity than Mg for plant nutrition, it is required to apply a mixture of both the limestones depending upon the Ca and Mg status of the soil (Haynes and Naidu 1998).

7.4.2 Gypsum

Gypsum is a rock like soft sulfate mineral composed of calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$). It is commonly used as an amendment to correct alkaline soils (to decrease pH). Gypsum is derived from natural deposit of calcium sulfate generally having 23% calcium and 18% sulfur. It is moderately water soluble, and in contrast to most of the salts it becomes less soluble at a higher temperature. By solubilizing in water the nutrient elements from gypsum can migrate to the root zone and improve the soil condition. In sodium accumulating clayey soils, where the soil structure is poor, gypsum can supply Ca^{2+}. Thus through an exchange reaction it enhances the flocculation of soil particles and improves the soil structure (Naidu and Rengasamy 1993). The application of gypsum along with mulch and earthworm was shown to remarkably improve the fertility of alkaline soils (Sarkar and Naidu 2015).

7.4.3 Clays and Clay Minerals

The application of clays or clay rich sub-soils to a light textured and/or water repellent soil is known as “claying” or “clay-spreading” (Sarkar and Naidu 2015). This technology was proven highly effective in preserving moisture in water repellent soils, and maintaining crop cultivation (Sarkar and Naidu 2015; Hall et al. 2010). When the compacted sub-soil clay layers are broken down to a depth of 35–50 cm and mixed with the topsoil, the technology is called “deep ripping” (Betti et al. 2015). Clay amendment can ameliorate water repellent sand plain soils, improve water and nutrient retention capacity, and enhance soil microbial activities (Shi and Marschner 2014), which have direct influence on nutrient use efficiency (Sarkar and Naidu 2015).

7.4.4 Zeolites

Zeolites (e.g., clinoptilolite) are naturally occurring aluminosilicate minerals that are used as both the sources of plant nutrients and soil amendments. They help in improving the input use efficiency by reducing the leaching and immobilization of plant nutrients (Gholamhoseini et al. 2013; Colombani et al. 2015). They can hold the plant available nutrients and water in their crystalline porous structures. Zeolites are also known as “molecular sieves” because of their ability to selectively sort molecules based primarily on the size exclusion process. They are more effective in reducing nutrient leaching, particularly potassium and nitrogen, in light textured soils due to having high cation exchange capacity (Sarkar and Naidu 2015). Zeolites with a high sodium content can be harmful to the soil structure, therefore a low-sodium mineral is always preferred to apply to the soil. Zeolites are commonly used as a soil amendment in agriculture particularly in Europe and Japan.

7.4.5 Waste Mica

Waste mica is a byproduct of mica mining activities and is produced during the cleaning of fresh mica, which is mainly used in the electrical industry. This material is usually dumped in the surrounding area of mica mines and as such has no use in agriculture. It is a 2:1 type clay mineral, comes under the muscovite group according to the clay minerals classification (Subba Rao and Brar 2002). The structure of mica is flake-like with a theoretical composition of $(OH)_4K_2(Si_6Al_2)Al_4O_{20}$. It contains a significant amount of potassium (8–10% K_2O), magnesium (5–22% MgO), and iron (5–20% Fe-oxides). The nutrients present in the layered silicate structure of mica are not easily accessible to plants because they are non-exchangeable to the soil solution. Sometimes powder form of the material is used as an amendment in highly weathered soil and as a source of K nutrition for plants. The K release behavior from the structure of mica was investigated previously by soil chemists and mineralogists, and it might depend on various conditions such as pH, dissolved organic acid concentration, temperature, microbial activity, and other cation concentration (Sugumaran and Janarthanam 2007; Grigis et al. 2008; Basak and Biswas 2012; Biswas and Basak 2014).

7.4.6 Rock Phosphates

Rock phosphate (apatite) is a sedimentary (sometimes igneous) rock having high amount of phosphorus in it. The sedimentary deposits are the predominant source of the rock and contribute about 80% of the total world production of rock phosphate. The physical and chemical properties of rock phosphates can be highly heterogeneous depending on the geological origin of the products. The presence of carbonate (carbonate apatite) and fluoride (fluoro apatite) in the rock phosphates have significant influence on the chemical properties and also determine its value as a source of plant nutrients (Bolan et al. 1990). There is no universal application recommendation for this amendment because numerous factors are associated with the P dissolution rate from the mineral. In general, it is considered as a slow release P source and a soil amendment in plantation crops under an acidic soil environment. The soil pH, particle size of the product, Ca content in soil, and cultural practices are considered as the most important parameters that affect P release from rock phosphates (Narayanasamy et al. 1981; Basak and Biswas 2016).

7.4.7 Diatomite

Diatomite is also known as diatomaceous earth, basically a silica-based mineral obtained from the skeletons of microscopic algae called diatoms. In lacustrine or marine sediments, it is formed by the continuous deposition of amorphous silica or opal from the dead body of diatoms (Antonides 1998). The fine powder of diatomite has quite similarity with pumice powder and has a notably low density due to having a high porosity. The dried diatomite is mainly composed of 80–90% silica, 2–4% alumina, and 0.5–2% iron oxide (Meisinger 1985). The application of diatomite can improve the aeration porosity in fine texture soils and capillary porosity in coarse texture soils.

7.4.8 Pyrites

Pyrite is an iron and sulfur containing mineral (FeS_2). It is found all over the world in igneous and metamorphic rocks and some places as sedimentary deposit as well. Pyrite is the major S source in developing countries of Asia. A detail chemical composition of agricultural grade pyrite shows that it contains appreciable quantities of zinc, copper, manganese, and iron which are likely to have significance in plant nutrition. Although iron pyrites have various physical forms such as crystalline, massive, or powdery, the powdery form of sedimentary type is chemically the most reactive. Agricultural grade pyrite is a by-product of the mining of acid grade pyrite. The low grade iron pyrite is not of any industrial use, but it has great potential for restoring the productivity of alkali wastelands (calcareous soil) and improving the fertility of soils (Castelo-Branco et al. 1999; Tozsin and Arol 2015). Like gypsum and elemental S, pyrites also have the dual role of amendment conditioner and fertilizer (Sarkar and Naidu 2015; Tandaon 1987).

7.4.9 Pumice

Pumice is a light, siliceous, and porous mineral that forms during the volcanic eruption. The mineral looks like sponge as an ample number of gas bubbles are formed inside the mineral structure. The finer fraction of the mineral can improve the water holding capacity of soils while the lighter fraction can increase the aeration porosity, which consequently can improve the total porosity in clayey soils. Pumice can be mixed with soil to provide a good aeration for the plant growth. It is also used in hydroponics as well as for preparation of the soil-less growing medium for plants.

7.4.10 Perlite

Perlite is also having the similar physical properties that originate from a quick heating during the volcanic eruption. It is amorphous in nature, mainly used in the preparation of light-weight potting mixtures. Its application is generally found in roof top gardening activities. In addition, the soil application of perlite can potentially improve soil physical properties like water holding capacity and aeration porosity.

7.5 Industrial Byproducts

The industrial byproduct materials are often added to soils for enhancing the physico-chemical properties that potentially can improve the crop yield and plant growth. The byproducts may contain carbonaceous materials that can enhance the water retention of soils and provide a congenial environment which supports the microbial activity. They can also supply the nutrients which are required as either essential or trace elements for plant production. Some of the products are also known to alter the soil reaction (pH) and structure (Table 7.3). They can be supplied to the soil either by surface application or homogeneous mixing with the topsoil. In numerous instances, the byproducts were reported to support an enhanced crop growth and yield through providing a soil medium with balanced nutrition and congenial physico-biochemical conditions.

Table 7.3 Industrial by products, their sources, and specific uses in agriculture

Industrial by products	Source	Uses
Fly ash	Coal industry	Ameliorate soil acidity Improve soil texture and reduce bulk density Amendment for pyritic mine tailings Waste land reclamation
Red mud	Alumina industry	Fix soil P and prevent leaching loss from sandy soil Ameliorate soil acidity and fix heavy metals
Basic slag	Steel industry	Act as a liming agent Slow release P fertilizer Increase soil porosity and hydraulic conductivity
Press mud	Sugar industry	Source of various nutrients Production of enriched compost

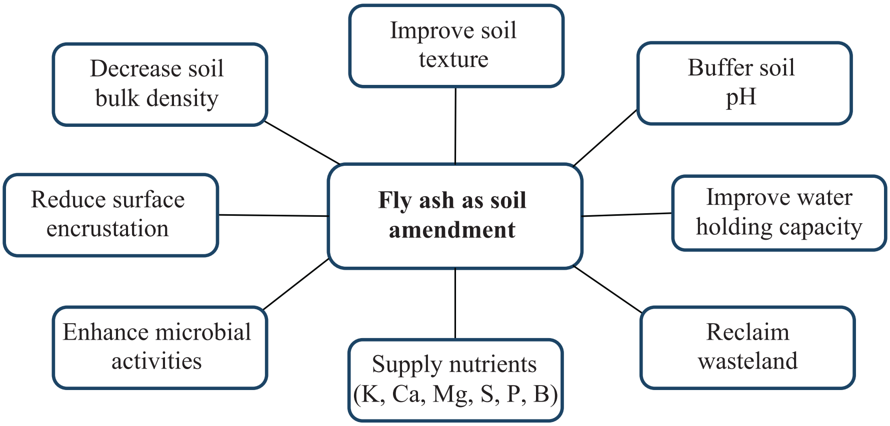

Fig. 7.3 Schematic diagram showing specific roles of fly ash as a soil amendment

7.5.1 Fly Ash

Fly ash, a waste of the coal industry, can be used as an ameliorant for improving the physical, chemical, and biological properties of problem soils. It also provides additional macro and micronutrients for plant growth. The combustion of powdered coal at a high temperature (400–1500 °C) generates the fly ash which is a mixture of amorphous ferro-aluminosilicate minerals. The fly ash powder can occur as very fine particles (average diameter of <10 μm) with high surface area. It has a low to medium bulk density. The beneficial effects of fly ash application to soils are shown in Fig. 7.3 (Kalra et al. 2003; Jala and Goyal 2006; Riehl et al. 2010; Ram and Masto 2014). It can be applied as an amendment to buffer the soil pH and maintain the optimum soil reaction for a healthy crop production. The addition of alkaline fly ash in acid soils may facilitate the release of nutrients such as S, B, K, P, Ca, Mg, and Mo by neutralizing the acidity of the soils. However, an excess increase in availability of B due to the application of fly ash may result in toxicity problems for crop production. Nevertheless, these issues can be addressed by choosing the appropriate stage of the weathered fly ash (Basu et al. 2009). The addition of fly ash generally improves the soil porosity and water holding capacity owing to its ability to decrease the bulk density of the soil. The reduction in the surface incrustation as a result of fly ash addition is attributed to the improvement in the hydraulic conductivity of soils which are amended with fly ash. Use of fly ash in combination with various types of organic manures can promote the microbial proliferation, and hence improve the enzymatic activities in soils. Furthermore, acid mine spoils can be neutralized with the application of fly ash amendment (Ukwattage et al. 2013).

7.5.2 Red Mud

Red mud is an alkaline byproduct of the aluminum (Al) industry. The alkalinity in the material is generated because during the Al extraction process the raw material bauxite is treated with caustic soda. The material is rich in iron (Fe) (25–40%) and Al oxides (15–20%). Due to its intrinsic chemical properties, its applicability to soil as an amendment can be confined under some specific conditions. When applied to soils, it can potentially alleviate the eutrophication issue in rivers and surface waters by locking phosphorus (P) (Liang et al. 2012; Summers et al. 1996a, b). The predominant alkali in red mud is sodium carbonate which is more soluble in the soil solution than the conventional liming material calcium carbonate. As a result, red mud can also be used as a liming agent to ameliorate soil acidity (Summers et al. 1996a). Its application to soils which are contaminated with heavy metals can also significantly decrease the metal uptake by plants (Friesl et al. 2003; Lombi et al. 2002; Castaldi et al. 2009).

7.5.3 Basic Slag

Basic slag is a byproduct of the steel making industry. It is largely composed of limestone or dolomite which adsorbs phosfate from the iron ore being smelted. Just after the manufacturing process a highly porous aggregate of the material is formed due to a rapid cooling in chilled water. The slag material is often alkaline in nature with a high pH value, which makes this material a good amendment for acidic soils. It can potentially increase the water movement and air porosity of soils, which provides a better plant growth condition. Due to its liming effect and slow P release behavior, slag can be valued as a fertilizer in gardens and farmlands (Negim et al. 2010; Pinto et al. 1995).

7.5.4 Press Mud

Press mud is an industrial waste available from sugar mills. The sugarcane press mud (SPM) is obtained following the filtration of the sugarcane juice. The residue is also known as press mud cake or filter cake. For every 100 tons of sugarcane crushed, about 3 tons of press mud cake is produced. The SPM contains appreciable amount of N (2–2.5%), Si, Fe, Mn, Ca, Mg, and P. Due to its considerable nutrient values it can be used as a fertilizer (Yang et al. 2013; Bhosale et al. 2012; Yaduvanshi and Yadav 1990). It can also improve the soil physico-biochemical properties (Yang et al. 2013; Bhosale et al. 2012; Yaduvanshi and Yadav 1990). By applying press mud into the soils for crop production, the issue of its disposal can be addressed. In conventional practices, it is usually burnt in brick kilns in the developing countries, which might potentially cause the wastage of millions of tons of nutrients. The quality of the SPM fertilizers can be improved many folds by co-composting the material with other organic matters such as distillery effluents and beneficial microorganisms.

7.6 Synthetic Amendments

Recently, functionalized super absorbent polymers or hydrogels have received considerable interests as one of the most exciting materials for improving soil water use efficiency (Sarkar et al. 2014; Arbona et al. 2005; Bai et al. 2010) and controlling release of agrochemicals (nutrients, pesticides, etc.) from designated products (Liu et al. 2007; Sarkar et al. 2015; Rudzinski et al. 2002). Hydrogels are three-dimensionally arranged lightly cross-linked networks of hydrophilic polymer chains that are water insoluble and capable of absorbing large amounts of aqueous fluids. The network can retain a large volume of water by swelling but without losing the structural dimension, and hence they are called superabsorbent polymers. The use of hydrogels as a soil conditioner for improving agricultural productivity has shown encouraging results and certain advantages of hydrogel are summarized in Fig. 7.4 (Arbona et al. 2005; Bai et al. 2010; Luo et al. 2009). They have been successfully applied to soils for improving growth of many tree species under drought conditions (Agaba et al. 2010; Orikiriza et al. 2009; Beniwal et al. 2011).

7.7 Unconventional Amendments

Fertilizers, organic manures, and composts alone do not govern the sustainability of a farming system, rather several soil amendments together may play a key role. Assorted by products from food and fiber industries are also used as soil amendments, which can be termed as alternative or unconventional amendments. Many plant by products (e.g., cottonseed meal (7% N), alfalfa meal (3% N), soybean meal (7% N),

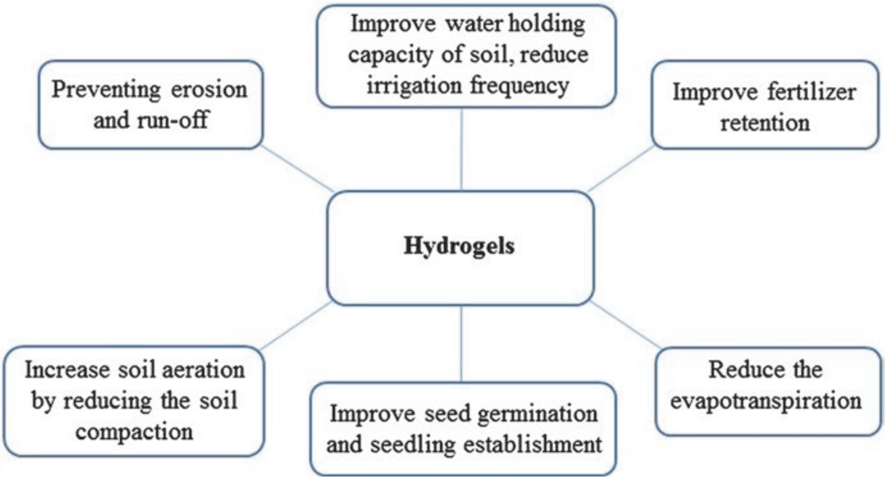

Fig. 7.4 Advantages of hydrogel amendment to soils

wood ash (2% P_2O_5 and 6% K_2O), leaf compost, fruit pomace (remaining after juice extraction)) and animal by products (e.g., blood meal (12% N), bone meal (27% P_2O_5), fish meal (10% N, 27% P_2O_5), feather meal (7–10% N), and leather meal (10% N)) are the few among many unconventionally used soil amendments. Granite and basalt dust, greensand, humates, and seaweed products also deserve special mentions (Sarkar and Naidu 2015).

7.8 Cost-Benefit Analysis of Soil Amendments

Although soil organic amendments (crop residues, farm yard manure, green manure, compost, etc.) are used mainly for enhancing the agronomic yield, they are equally important for the maintenance of the soil fertility while enhancing C sequestration. Nutrient management through organic farming also improves nitrogen fixation and reduces nutrient leaching (Pandey and Singh 2012). Apart from increasing the plant growth, soil amendments help to protect the natural resources in a sustainable manner. Therefore, the benefit of soil amendments is additive which is not always measurable in economic terms.

Biochar is a costly amendment as compared to others mainly due to its high production cost. The cost of biochar can be reduced by increasing the production scale. However, the application of biochar can be profitable when used for growing cash crops that give a high return, or when applied on a small-scale high-value farming (e.g., greenhouses, tree nurseries, floriculture, etc.) (Kulyk 2012). The expensive soil amendments such as wood biochar, clays, and rock phosphate may not provide a high incentive to the farmers within the first cropping cycle, but can be economically viable in the long run (5–7 years) (Mekuria et al. 2013). On the contrary, inexpensive amendments such as compost and manure may translate into quick visible agronomic benefits.

7.9 Conclusions

Irrespective of their origin and classification, amendments play multiple roles in improving the physical, chemical, and biological properties of soils. All these potentially enhance the soil productivity and health. This is an era when biomass and material recycling for bioenergy production is considered as one of the major pillars for sustainable development. Many of the soil amendments enable utilization of by products of other industries and thus promote resource recycling. The locally available and inexpensive soil amendments can potentially increase the agricultural productivity in a sustainable manner. This consequently can raise the income of smallholding farmers. The decision makers should promote the adoption of low cost soil amendments by the agricultural and forestry growers. The best management practices should be followed in order to harness the optimum benefits of soil amendments in agricultural and forestry production systems, which will potentially contribute to the productivity growth and food security.

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Resource Conservation Technologies for Sustainable Soil Health Management

8

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Abstract

The soil health degradation is one of the important challenges before farmers, researchers and policy makers. This problem has resulted in plateaued or even declining agricultural productivity especially in arid and semi-arid tropics. It also threatened the livelihood of small and marginal farmers in these areas. This chapter describes how resource conservation technologies like minimum soil disturbance, adequate soil cover, crop rotations and agroforestry are useful in sustaining soil health and crop productivity especially in fragile areas.

Keywords

Resource conservation technology • Conservation agriculture • Soil health

8.1 Introduction

Present day agriculture is facing major challenges viz., depleting natural resources, negative impacts of climate change, increasing input costs for achieving food security and agricultural sustainability. The major cause for steady decline in agricultural sustainability includes intensive cultivation with conventional tillage, reduction in soil organic matter, loss of soil structure, water and wind erosion, reduced infiltration rate, formation of soil crust and compaction and continuous monocropping. Over the years soil and water resources are continually overexploited leading to

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reduction in use efficiency of fertilizer, irrigation and energy. Rice-wheat cropping system is the predominantly practiced by farmers in Indo-Gangetic Plain region of India with unsustainable, conventional land preparation and sowing practices not only disturbs the soil environment but also leads to atmospheric pollution. During green revolution era, food grain production enhanced mainly from increase in rice-wheat area as well as the system productivity. Continuation of the same rice-wheat system without appropriate crop rotation over the last 50 years has aroused many problems which have restricted the ability of natural resources to produce to the higher yields matching with future food grain requirement of the country. The deteriorating production and sustainability of the rice-wheat systems are evident from either stagnation or decline in soil physical environment, excessive mining of essential plant nutrients from soil. Use of water to irrigate rice and wheat has surpassed the natural ability of the ecosystems to replenish itself. In recent years growing declaration in total factor productivity and deterioration of soil health under cereal-based cropping system has necessitated for diversification of existing cropping systems with conserving the natural resources efficiently. Therefore, simple change or management of cultivation practices through eliminating or modifying the unsustainable conventional agricultural practice like conventional tillage, removal of all organic material, monocropping are needed for gain in productivity in near future while sustaining the natural resource base.

The term soil health has been used in relation to sustainability in agriculture. In totality soil health describes its physical, chemical and biological properties and their integration. Soil quality is a term used to describe physical attributes of a soil. These characteristics are simple traits like soil colour to more complex properties like fertility, erodibility and compatibility. Soil health is manifested through vital soil properties or through key soil functions. A healthy soil is supposed to have values of key parameters or key soil functions in the desirable and optimum range. Thus, the concept of soil health or soil quality is based purely on soil properties and it sustains the plant, animal and human being, maintains the quality of water and air. Besides water, of all the risks to sustainable growth of agriculture, low soil fertility is the most serious threat. Intensive agricultural practices with tilling of soils can lead to gradual deterioration in soil physico-chemical and biological properties and consequently reduction in crop productivity. Thus, practice of conventional tillage operation over few decades has been questioned because of the soil erosion from cultivated land after tillage. It is a well-known fact that injudicious use of applied farm inputs and overexploitation of natural resource base, mainly land and water had led to some of the following major soil health issues: loss of soil organic carbon, soil salinization, ground water depletion, soil compaction and increase in the runoff rate leading to more soil erosion. Deterioration of soil physical and chemical properties and water quality due to nutrient mining and pollution of ground water in some locations due to over application of nitrogenous fertilizers and harmful to environment through crop residue burning and pesticide use have been emphasized (Pingali and Shah 2001; Gupta et al. 2003). In eastern IGP region, rice-wheat system is mainly practiced by operating intensive labour and less mechanization. Crop residue removal/burning in India is a serious problem, leading to widespread problems of secondary and micronutrient deficiency, explaining why we have the "yield stagnation" scenario presented so often. The current challenge is addressing the issue of small land holdings and poverty amongst these farmers. Unfortunately, poverty has made crop biomass an attractive fuel for farm homes, and an additional source of income. As farm size increases, alternative cooking/heating fuels will hopefully become more popular (gas/electricity) and crop biomass will no longer be in demand.

Maintaining and protecting soil health under intensive land use system and in the era of faster economic development is a major challenge for sustainability of agriculture resource use especially in the developing countries like India. The basic assessment of soil health is necessary to evaluate the changing trends following different land use and management interventions. Soil health is adversely affected due to nutrient imbalance in soil, excessive fertilization, soil pollution and soil loss processes (Swaminathan 2006). The soil health concept has evolved with an emphasis on understanding the soil processes. Soil physico-chemical and biological properties are sensitive to management practices can be used as indicators in measuring the soil health. Soil health (e.g. physical, chemical and biological) is determined by soil characteristics, which can be altered by management practices followed under various cropping systems (Liebig et al. 2004). Lal (1994a, b) suggested that soil degradation caused by improper use of land and soil particularly its management should be quantified by measuring management induced changes in soil properties and their impacts on actual and potential productivity. Establishing and understanding the cause–effect relationship between soil properties and processes on the one hand and crop productivity and environmental moderating functions on the other is crucial to enhancing soil productivity, restoring degraded lands and improving environmental quality. Under such scenario, resource conservation technologies (RCTs) assume great significance.

8.2 Resource Conservation Technologies for Soil Health

Soil affects not only production, but also the management of other natural resources which are associated with soil, such as water. Soil structure is strongly correlated with the organic matter content, which gives life to the soil. Organic matter stabilizes soil aggregates, provides feed to soil life and acts as a sponge for soil water. With intensive conventional tillage-based agriculture systems, the organic matter of soil is steadily decreasing, leading to a decline in productivity, followed by the visible signs of degradation and finally desertification. We are all well aware that most of the biological, chemical and physical properties attribute to improved soil health come from the maintenance or improvement of soil organic matter content in soil (Hati et al. 2008; Mandal et al. 2007). Soil organic matter not only improves soil tilth, water infiltration, water storage, CEC and microbial activity but also the availability of macro, secondary and micronutrient. There is a deterioration of soil health parameters, such as soil organic C, soil biodiversity, soil physical properties and soil fertility. There is a gap of more than 10–12 million tonnes of NPK between the nutrients depleted by crops and nutrients added through fertilizer. Farmers in the developing countries use low inputs because of their socio-economic constraints and serious problems of drainage during heavy rains and rainwater management in drought situations. There is decrease in yield response of high yielding varieties to increased doses of fertilizer in the Indo-Gangetic Plains can be attributed to poor soil health resulting from overexploitation of natural resource base. It has been observed that in Indian states of Uttaranchal and Haryana, the organic carbon content in soils reaches minimum values of <0.1% (PDCSR 2005). Conserving the land resources for agriculture and livelihood is necessary to comprehend the extent of degradation across the geo-political regions of India. In India, Jammu & Kashmir and Nagaland states are having maximum share of their land (94%) under degradation. This is primarily due to large areas under mountains, cold deserts and other such degraded lands. Agriculturally prominent states like Uttar Pradesh (63%), Madhya Pradesh (50%) and Karnataka (46%), the extent of land degradation is of great concern. Ecological or natural farming either through conservation agriculture or any other form will help check land degradation (Kumar et al. 2011). Long-term trials in South Asia clearly show that well managed, high yield cropping systems, which return crop residues to the field, significantly improved the soil organic matter and related soil biological, chemical and physical properties (Singh and Singh 2001; Singh et al. 2016). Work with conservation tillage and nutrient management further indicates that not only is soil organic matter improved, but the system can also support current or higher yields, and reduce associated GHG emissions per tonne of grain production (Sapkota et al. 2014).

8.3 Resource Conservation Technologies: The Concept, Practices and Principles

The term resource conserving technologies (RCTs) and conservation agriculture has a sharper distinction. Resource conserving technologies refers to those practices or technologies that enhance resource or input use efficiency such as new varieties that use nitrogen more efficiently, zero or reduced tillage practices that save water, etc., may be considered as RTCs. However, the term conservation agriculture (CA) refers to the system of raising crops in no-tillage with retention of crop residues on the soil surface. CA is a resource-saving agricultural production system that aims to achieve production intensification and high yields while enhancing the natural resource base through compliance with three interrelated principles, along with other good production practices of plant nutrition and pest management (Abrol and Sangar 2006).

Conventional agriculture based on traditional tillage and being highly mechanization has been accused of being responsible for soil and water erosion problems, surface and underground water pollution, and more water consumption (Wolff and Stein 1998). Besides, degradation of land resources, reduction in wildlife and biodiversity, low energy efficiency and contribution to global warming problems and climate change in agriculture (Boatman et al. 1999). Conservation agriculture (CA) is the best way for sustainability of annual and perennial crops, and cropping systems based on conservation tillage with crop residue management/cover crops, in order to offer a permanent soil cover which in turn increases the organic matter content in soil. The beneficial impacts of conservation farming practice on the global environment (soil, air, water and biodiversity) compared to traditional agriculture (Derpsch et al. 2010, 2011) are widely reported. CA promotes that most soils to have a richer biological activity and biodiversity, a better structure and cohesion, and a very high natural physical protection against weather parameters (raindrops, wind, dry or wet periods). Soil erosion is therefore highly reduced, soil agronomic inputs transport slightly reduced, while pesticide bio-degradation is enhanced. It protects surface and ground water resources from pollution and also mitigates negative climate effects. Hence, CA provides excellent soil fertility and also saves money, time and fossil fuel. It is an efficient alternative to traditional agriculture, attenuating its drawbacks.

Conservation agriculture (CA) as described by FAO (http://www.fao.org.ag/ca) is a concept for resource-saving agricultural crop production, which is based on enhancing natural and biological processes above and below the ground on a long-term basis. The aim of conservation agriculture is to conserve, improve and make more efficient use of available natural resources through integrated management of available soil, water and biological resources combined with external inputs. Adoption of CA practices reduces the soil degradation processes and builds up soil fertility through increase in water holding capacity, improves the infiltration rate of rainwater and enhances ground water storage, enrichment in soil organic carbon (SOC) and microbial diversity in the rhizosphere. It avoids the power-intensive soil tillage operation, thus reducing the drudgery, labour and energy required for crop production by more than 50% of the small scale farmers. CA has a long-term and broader perspective, which goes beyond yield improvement. Introduction of conservation agriculture (resource conserving technologies) in existing crops and cropping systems is an important breakthrough for sustaining productivity, conservation of natural resource base and economic growth of farmers. These conservation agriculture technologies mostly target the two crucial natural resources: water and soil, but some also affect the efficiency of other production resources and inputs (e.g. labour, farm power and fertilizer). Some of the more popular RCTs along with their effect on soil health are described below.

8.4 Minimum Soil Disturbance Through Conservation Tillage

Conservation tillage refers to any tillage and planting system that maintains at least 30% of the soil surface covered by residues after planting to reduce water erosion or where wind erosion is the primary concern maintain at least 1000 kg/ha of small grain residues equivalent on the surface during the critical wind erosion period. Conservation tillage (CT) is described as tillage practices specifically intended to reduce soil disturbance during seedbed preparation with the objective of improving soil organic matter, structure and stability, and conserving soil moisture. It is intended to conserve soil, water, energy, and protect water and environmental quality. Conservation tillage systems involves a variety of techniques, including no-till, minimum till, ridge till, chisel plow, mulch till, etc. These tillage techniques can be key component of a sustainable agricultural system, as it can be used to decrease soil erosion losses, enhance input use efficiency, increase soil organic matter buildup and reduce the cost of production and environmental degradation. It is important to remember that anything that is done to decrease soil erosion losses also reduces the need to add fertilizer and water to soils with fact that most of organic matter content present in top soil. Conservation tillage also decreases water pollution (less soil erosion) and saves fossil fuel energy and thus decreases CO_2 emissions and cost of production compared to conventional tillage systems.

8.4.1 No-Tillage or Zero Tillage

In no-tillage, soil is completely left undisturbed from harvest to planting except sowing nutrient application. Weed control is only by herbicide. No-till farming a technique of conservation tillage, synonymously called as zero tillage or direct sowing/dibbling, is a way of growing crops from year to year without disturbing the soil through tillage. No-tillage system has developed to maintain soil health for sustainable agriculture and economic alternative to current crop production practices. It contributes to carbon sequestration through storage of soil organic matter in the soil of crop fields (Bayer et al. 2006). Under conventional tillage soil layers turned up and down, air mixes in and soil microbial activity dramatically increases over baseline levels which resulted in faster oxidation and breaking of organic matter and carbon is lost from the soil into the atmosphere. In addition to keeping carbon in the soil, no-till farming reduces nitrous oxide (potential GHG that stays in the atmosphere for 120 years) emissions by 40–70%, depending on rotation (Omonode et al. 2011).

8.4.2 Reduced or Minimal Tillage

Little soil disturbance before sowing to break the crust, loosen compact soil and prepare seedbed. Weed control by herbicides or some secondary tillage. Minimum tillage is also a technique of conservation tillage system like strip till with the goal of minimum soil manipulation necessary for a successful crop production. It is a tillage method that does not turn the soil over, reduces the evaporative loss of water, enhances the water holding capacity and conditioned the soil temperature based on surface residue. It is contrary to intensive tillage, which changes the soil structure by plough.

8.4.3 Ridge Tillage or Raised Bed Planting

In this conservation tillage technique, equipment is used to move soil so the crop row is slightly elevated. This system is usually used on soils that may drain poorly or warm slowly in the spring. The rows are maintained in the same location each season and at planting the top of the ridge is leveled off. Planting on these ridges provides warmer conditions for early plant growth. In most cases, the residue on the soil surface between ridges is not disturbed and provides for moisture conservation during the season. Furrow irrigated raised bed (FIRB) is also a ridge tillage technique popularizing in Indo-Gangetic Plan (IGP) for maize-based cropping systems although it is a common practice of growing crops in western countries (Gupta et al. 2002).

8.4.4 Mulch Tillage

Tillage is practiced only to sow the crop, equipments don't bury the crop residues. Weed control by herbicides or some secondary tillage. Mulch tillage also called stubble mulch tillage is the practice of managing the amount, orientation and distribution of high percentage of plant residues on the soil as cover throughout the year. Mulch tillage technique prevents the soil erosion (more effective for wind erosion), reduces soil compaction, improves soil tilth and air quality, organic matter is added to soil, improve water quality and save time and money. Hobbs et al. (2008) clearly compared the conventional tillage and conservation tillage for various issues (Table 8.1).

Table 8.1 A comparison of traditional tillage (TT), conservation tillage (CT) and conservation agriculture for various issues

Issues	Traditional tillage (TT)	Conservation tillage (CT)
Practice	Disturbs the soil and leaves a bare surface	Reduces the soil disturbance in TT and keeps the soil covered
Erosion	Wind and soil erosion: maximum	Reduced significantly
Soil physical health	The lowest of the three	Significantly improved
Compaction	Used to reduce compaction and can also induce it by destroying biological pores	Reduced tillage is used to reduce compaction
Soil biological health	The lowest of the three owing to frequent disturbance	Moderately better soil biological health
Water infiltration	Lowest after soil pores clogged	Good water infiltration
Soil organic matter	Oxidizes soil organic matter and causes its loss	Soil organic buildup possible in the surface layers
Weeds	Control weeds and also causes more weed seed to germinate	Reduced tillage control weeds and also exposes other weed seeds for germination
Soil temperature	Surface soil temperature More variable	Intermediate in variability
Diesel use and cost	Diesel use: High	Intermediate
Production costs	Highest	Intermediate
Yield	Can be lower where planting delayed	Yields same as TT

Source: Hobbs et al. (2008)

8.5 Conservation Tillage and Soil Health

In conventional tillage practice (turning over of the soil), bare soil is exposed to the erosive action of the water and winds, which is the major causes of soil loss. Under conservation tillage, the crop residue buffers the raindrop energy, so water has less erosive force when it reaches the soil. This protection by residue along with the rougher surface provided by the residue facilitates infiltration and decreases runoff that carries soil and nutrients with it. In addition macropores, which are the major route for water movement through soil, get disturbed in tillage but remain intact under conservation tillage hence, enhance water infiltration, decrease runoff and conserve water and fertilizers. An important benefit of no-till production system is greater soil organic matter concentrations, especially near the soil surface (Dick 1983; Lal et al. 1980). It was observed by Hargrove and Fyre (1987) that soil organic matter accumulation is significant with no-till management, and the degree of accumulation depends largely on the amount of organic carbon returned to the soil (Table 8.2).

Direct seeded rice alone gave about 0.5 t/ha lower yields than transplanted rice in rice-wheat cropping system (Sharma et al. 2012). However, the loss was compensated when brown manuring with sesbania was done or greengram residues were incorporated in previous summer. Wheat yields were similar under zero-till wheat with rice residues left and conventionally tilled crop. System productivity and net returns were comparable under direct seeded rice with brown manuring followed by ZT wheat with rice residues, and conventional practice (Table 8.3).

Efficient use of water through conservation agricultural practices of residue management and zero tillage are most appropriate practical ways to restore the soil fertility (Pasricha 2014). Such practices, on long-term basis, help in sequestering organic C in soil and recycle part of the nutrients. These practices thus help in maintaining the quality of environment by preventing the in-field burning of the crop residues (Table 8.4). Average water use efficiency in terms of kg grain/ha/mm is higher by 16% in no-tillage as compared to conventional tillage (Table 8.5). Saving in irrigation water in rice-wheat cropping system is important, as rapid depletion of ground water and constant recession in the water table is the greatest threat to sustainability of rice-wheat cropping system in Indo-Gangetic plain. Conservation tillage and no-tillage systems can substantially improve the water holding capacity of these largely light textured soils by increasing the proportion of rainfall infiltrating into the soil (Table 8.6). Due to mulching effect of residue,

Table 8.2 Influence of cropping sequences and tillage practice on soil organic C and N concentrations in the surface of soil

Crop sequence	Tillage practice	Organic C (%)	Organic N (%)
Wheat-soybean	Conventional	1.4	0.12
Wheat-soybean	No-till	1.6	0.15
Clover-soybean	Conventional	1.9	0.14
Clover-soybean	No-till	2.2	0.17

Table 8.3 Conservation agriculture technologies in basmati rice (PRH 10)–wheat (HD 2894) cropping system at New Delhi

Treatment	Rice grain yield (t/ha)	Wheat grain yield (t/ha)	System productivity (t/ha)	Net returns ($\times 10^3$/ha)	Irrigation water productivity (kg rice/ha-mm)
DSR – ZT wheat	4.90	4.62	13.34	112.21	5.97
DSR – ZT wheat + RR	5.15	4.80	13.97	17.50	6.12
DSR + BM-ZT wheat	5.08	4.68	13.72	115.75	5.58
DSR + BM – ZT wheat + RR	5.32	4.88	14.35	121.68	6.20
DSR – ZT wheat – GG	5.18	4.78	15.77	128.42	6.22
DSR – ZT wheat + RR-GG	5.45	4.95	16.56	131.26	6.35
TPR – ZT wheat	5.55	4.88	14.76	120.13	3.75
TPR – CT wheat conventional	5.58	5.07	15.00	122.15	3.66

Source: Sharma et al. (2012)
DSR direct seeded rice, *TPR* transplanted rice, *BM* brown manuring with sesbania, *GG* greengram, *ZT* zero tillage, *CT* conventional tillage, *RR* rice residues

Table 8.4 Crop residue and nutrient returned from rice straw

Tillage	Crop residue (t/ha)		Residue (kg/ha)			
	Above ground	Root mass	C	N	P_2O_5	K_2O
Conventional till	–	6.86	3090	36.4	17.28	128
No-till	3.13	6.87	4340	53.0	25.19	187

Source: Pasricha (2014)

Table 8.5 Grain yield, harvest index and water use efficiency in wheat under two tillage treatments

Tillage	Grain yield (t/ha)	Harvest index (%)	Water use efficiency (kg grain/ha/mm)
Conventional till	5.95	44.0	7.02
No-till	6.07	46.2	8.14

surface evaporation and erosion losses also decrease. This would increase crop yields substantially and also enhance nutrient uptake due to greater attention of added fertilizers.

Rice-pea cropping sequence recorded 2143 kg Rice Equivalent Yield (REY) from 2000 m^2 area, whereas, the REY with rice-lentil sequence was 1284 kg from the same area compared to 652 kg under FP (Das et al. 2014). Thus, enhancement in Rice Equivalent Yield (REY) was 229% and 97% with rice-pea and rice-lentil

Table 8.6 Profile moisture content by depth after wheat as a function of tillage treatment

	Conventional till		No-till	
Soil depth (m)	(%)	(mm)	(%)	(mm)
0–0.15	1.74	3.92	2.25	5.06
0.15–0.30	3.80	8.55	4.52	10.17
0.30–0.60	5.03	22.64	6.42	28.89
0.60–1.20	7.34	66.06	9.84	88.56
0–1.20	–	101.17	–	132.68

Table 8.7 Rice equivalent yield (REY), water use efficiency (WUE) and water productivity of rice-based cropping systems

		WUE (kg/ha/mm) based on		Water productivity	
Farming practice	Rice equivalent yield (kg/2000 m^2)	ETc	Rainfall	Kg/m^3 water	Rs/m^3 water
Conservation agriculture					
Rice-pea	2143	19.69	1.28	0.64	9.57
Rice-lentil	1284	12.34	0.73	0.34	5.62
Farmers practice					
Rice fallow	652	5.99	0.36	0.18	2.66

Table 8.8 Maize equivalent yield, water use efficiency and water productivity of rice-based cropping systems

		WUE (kg/ha/mm) based on		Water productivity	
Farming practice	Maize equivalent yield (kg/2000 m^2)	ETc	Rainfall	Kg/m^3 water	Rs/m^3 water
Conservation agriculture					
Maize-French bean	1413	11.58	0.64	0.32	6.59
Maize-rapeseed	768	6.98	0.47	0.23	3.50
Farmers practice					
Rice fallow	528	6.23	0.32	0.16	1.80

compared to monocropping of rice, respectively (Table 8.6). Such high increase in REY under rice-pea/lentil sequences were due to comparatively higher price of lentil and higher green pod yield of pea. The Water Use Efficiency (WUE) and Water Productivity also enhanced substantially under rice-pea/lentil system compared to Farmers Practice (FP) of monocropping rice (Table 8.7). Maize-French bean sequence recorded highest Maize Equivalent Yield (MEY) of 1413 kg followed by maize-rapeseed sequence (768 kg) in compared to maize monocropping (528 kg). Thus, maize-French bean by 168% whereas, maize-rapeseed sequence enhanced MEY by 45% (Table 8.8). The maximum WUE and WP were recorded with maize-French bean (11.58 kg ha mm and 0.32 kg m water, respectively) followed by

Table 8.9 Soil profile moisture distribution, conservation, wheat grain yield and WUE as influenced by various maize post-harvest straw and tillage management practices

Treatment	Water use mean (mm)	Moisture conservation (mm)	Wheat grain yield (kg/ha)	WUE (kg/ha/mm)
T_1	173	–	1327	4.71
T_2	164	09	1362	4.73
T_3	138	35	2011	6.49
T_4	112	61	2537	7.71
T_5	149	24	1611	5.25
T_6	143	30	1819	5.73
T_7	142	30	1854	5.97
LSD (P = 0.05)	6.7		88	0.37

T1 maize harvesting at 30 cm height and tillage at the time of wheat sowing, *T2* maize plants left standing in the field after removal of cobs and tillage at the time of wheat sowing, *T3* tillage immediately after maize harvest, *T4* T_3 plus-application of maize stover mulch at 5 t/ha up to wheat sowing, *T5* tillage after 15 days of maize harvest, *T6* soil surface covered by maize stover mulch at 5 t/ha up to 15 days after maize harvest-plus-tillage, *T7* maize plants left standing in the field up to 15 days after removal of cobs-plus-tillage

maize-sequence (6.98 kg ha mm and 0.23 kg m water) compared to monocropping of maize (6.23 kg ha mm and 0.16 kg m water).

Sharma et al. (2013) reported that data on water loss between maize harvesting and wheat sowing show that plots treated after maize harvesting practices those caused moisture conservation (tillage and mulching) reduced the water losses from the soil profile (0–75 cm) and conserved more moisture for the use of succeeding wheat crop as compared to other treatments (Table 8.9). Tillage reduced the water losses due to evaporation as compared to no-tillage. However, reduction in soil moisture losses further increased when maize straw mulch was applied at 5 t/ha after undertaking tillage operations as compared to tillage alone. It revealed that imposition of tillage treatment (T_3) conserved more moisture as compared to no-tillage (T_1), However, conservation was maximum when the soil surface is covered with maize stover mulch at 5 t ha up to wheat sowing (T_4). Higher increase in wheat grain yield achieved due to moisture conservation practices (mulching and tillage) and was significantly higher than non-mulched and no tilled plots. The relationship between additional wheat grain yields due to soil moisture conservation showed a linear relationship. It was found from the relationship that per unit (mm) increase of soil moisture conservation, additional wheat grain yield of 23.2 kg can be achieved in this soil plant climate condition (Fig. 8.1).

8.6 Maintaining Soil Cover

Maintaining a permanent or semi-permanent soil cover with any organic material is necessary to protect the soil physically from sun, rain and wind and to feed soil biota. Adequate soil cover can be maintained by cover crops, mulching and crop residue management.

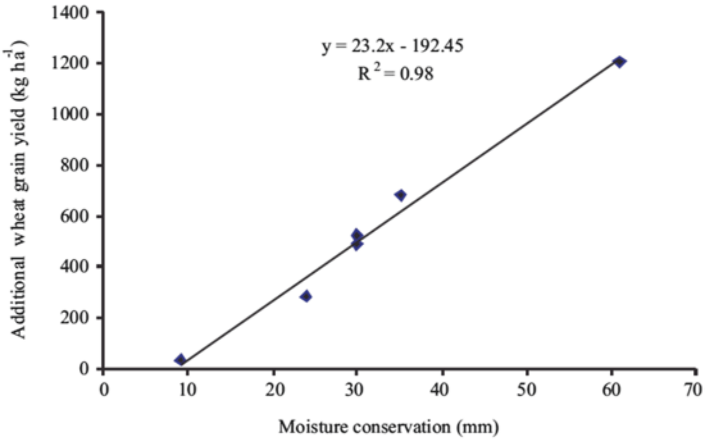

Fig. 8.1 Additional wheat grain yield due to soil moisture conservation

8.6.1 Cover Crops

Cover crops must be multi-purpose crops and must be carefully managed through appropriate technologies. For example, *Crotalaria juncea* L. is a good source of fibre, very effective for nematode control as well as soil properties and fertility improvement (N fixation, high level of organic matter, etc.). Good ground cover by crop canopy especially legumes protects the soil and minimizes soil erosion. Generally cover or smother crops add organic matter into the soil. Besides conserving soil and moisture, the cover crops hold those soluble nutrients, which are lost by leaching. Among the legumes cowpea has been found to produce maximum canopy in rainy season followed by horsegram, greengram, blackgram and sesbania. These crops give early and dense ground cover up to the extent of 85% which generally coincides with peak rate of runoff. The permanent soil cover through dense crops, mulch or green manure cover crops complements the effects of zero tillage by supplying substrate for soil organic matter buildup and for the soil life which is facilitated by not disturbing the soil. By protecting the soil surface, the mulch reduces evaporation, avoids crusting and suppresses weed growth. Problems experienced in direct seeding or zero tillage (applied in isolation) are thus reduced. It should also be noted that adoption of zero tillage and direct seeding facilitates the management of residues which in conventional systems are often considered a problem.

8.6.2 Mulching

Mulch is simply a protective layer of any material that is spread on top of the soil. Mulches can either be organic or inorganic. It prevents splash erosion and surface runoff along with improves soil texture by adding organic matter. Tillage and mulching management in maize-wheat cropping sequence revealed that polyethylene

Table 8.10 Effect of tillage and mulching on maize and wheat grain yield (t/ha)

Treatment	Maize yield					Wheat yield				
	Tillage					Tillage				
Mulching (M)	CT	MT	NT	RB	Mean	CT	MT	NT	RB	Mean
Control	1.50	1.38	1.29	1.27	1.36	0.46	0.40	0.32	0.38	0.39
Straw	2.08	2.05	1.86	2.0	2.0	0.57	0.54	0.49	0.52	0.53
Polyethylene	2.35	2.35	2.07	2.14	2.23	0.59	0.57	0.52	0.56	0.56
Soil	2.07	2.02	1.82	1.96	1.97	0.52	0.50	0.48	0.5	0.50
Mean	2.0	1.95	1.76	1.84		0.54	0.50	0.45	0.49	
CD (*P* = 0.05)	T 0.13		M 0.15		T × M NS	T NS		M NS		T × M 0.22

RB raised bed, *T* tillage, *M* mulching, *CT* conventional tillage, *MT* minimum tillage, *NT* no-tillage

Table 8.11 Effect of tillage and mulching options on infiltration rate (cm/h) during *kharif* in maize

Treatment	30 DAS					At harvest				
	Tillage (T)					Tillage				
Mulching (M)	CT	MT	N T	RB	Mean	CT	MT	N T	RB	Mean
Control	0.75	0.88	0.95	0.83	0.85	0.52	0.61	0.65	0.58	0.59
Straw	0.95	1.10	1.28	1.03	1.09	0.61	0.70	0.74	0.67	0.68
Polyethylene	1.05	1.25	1.35	1.15	1.20	0.64	0.74	0.78	0.70	0.71
Soil	0.92	1.08	1.18	0.99	1.04	0.59	0.67	0.72	0.65	0.66
Mean	0.92	1.08	1.18	0.99	1.04	0.59	0.67	0.72	0.65	0.66
CD (*P* = 0.05)	T 0.068		M 0.07		T × M NS	T 0.059		M 0.065		T × M 0.052

mulch recorded the highest grain yield of maize followed by straw mulch (Sharma et al. 2009). A significant variation was found in maize mulching treatment. Grain yield in CT and MT was statistically at par but both the tillage methods produced significantly greater grain yield than in RB and NT. The residual effect of tillage and mulching in rainy season was non-significant on the yield of wheat during winter season. However, the highest grain yield of maize and wheat was observed in CT which was statistically on par with MT, RB and NT (Table 8.10). Mulch application significantly increased the maize and wheat yield. This was due to decrease in evaporation and availability of adequate soil moisture for longer period. Under limited moisture supply, through the conservation of moisture and regulation of soil temperature, this in turn increased the maize and wheat yield. Inadequate moisture supply under no mulching resulted in low grain yield which was due to deleterious effect on most of the physiological process of the crop. Various tillage and mulching treatments had significant effect on infiltration rate (Table 8.11). Conventional tillage caused a significant decrease in infiltration rate both during rainy and winter

Table 8.12 Bulk density, total porosity of investigated soil and wheat grain yields for tillage and mulch treatments

Treatment	Bulk density (g/cm^3)	Total porosity (cm^3/cm^3)	Grain yield (t/ha)
0–10 cm			
RZ	1.35a	0.466b	5.54b
RM	1.25b	0.508a	6.79a
CZ	1.26b	0.503a	6.53a
CM	1.23b	0.514a	7.00a
10–20 cm			
RZ	1.38a	0.458b	
RM	1.37a	0.463b	
CZ	1.25b	0.508a	
CM	1.24b	0.512a	

Means in columns for particular soil layer followed by the same letter are not significantly different ($P < 0.05$)

RZ reduced tillage but zero mulching, *RM* reduced tillage and mulch, *CZ* conventional but zero mulching, *CM* conventional tillage and mulch

seasons. Infiltration rate was 17.4% and 13.5% higher in minimum tillage than the conventional tillage at 30 DAS and harvesting of the maize crop, respectively. This was due to the conservation tillage systems in which >30% of soil surface is covered with plant residues. This natural mulch reduced evaporation of soil water and increased the infiltration rate. The highest infiltration rate was observed with applying polyethylene mulch on soil followed by straw mulch, soil mulch and no mulch at 30 DAS and at harvest of maize crop.

Glab and Kulig (2008) reported that reduced tillage without mulch (RZ) or mould board plough increases the soil density what is widely reported particularly in no-tillage system. This relation was confirmed in the 10–20 cm soil layer (Table 8.12). However, in the upper, 0–10 cm soil layer with mulch (RM) the bulk density decreased and reached the similar value as those obtained at conventional tillage (CZ and CM). The inverse effect was recorded in total porosity; mulch addition increased the total porosity in more compacted soil under reduced tillage (RM). Residue mulch decreased bulk density in rather compacted soils particularly in no-tillage system what can be ascribed to higher soil carbon content and biotic activity. The conventional tillage resulted in higher yields (CZ and CM treatments), compared with reduced tillage treatments (Table 8.9). The significant interaction between tillage and mulching was observed. When conventional tillage was applied (CZ and CM) there was no influence of mulching on plant yield. The favourable effect of mulching was observed at reduced tillage (RM).

Yadav et al. (2009) conducted a study on effect of *Trichoderma viride* inoculation in ratoon sugarcane with three trash management practices, i.e. trash mulching, trash burning and trash removal. Soil microbial biomass carbon (SMBC) at harvest was higher than the initial value in all plots except in the plots with trash burning/removal without application of *Trichoderma*. The maximum increase (40 mg C/kg soil) over initial status was noticed in trash mulch plots with *Trichoderma* (Fig. 8.2).

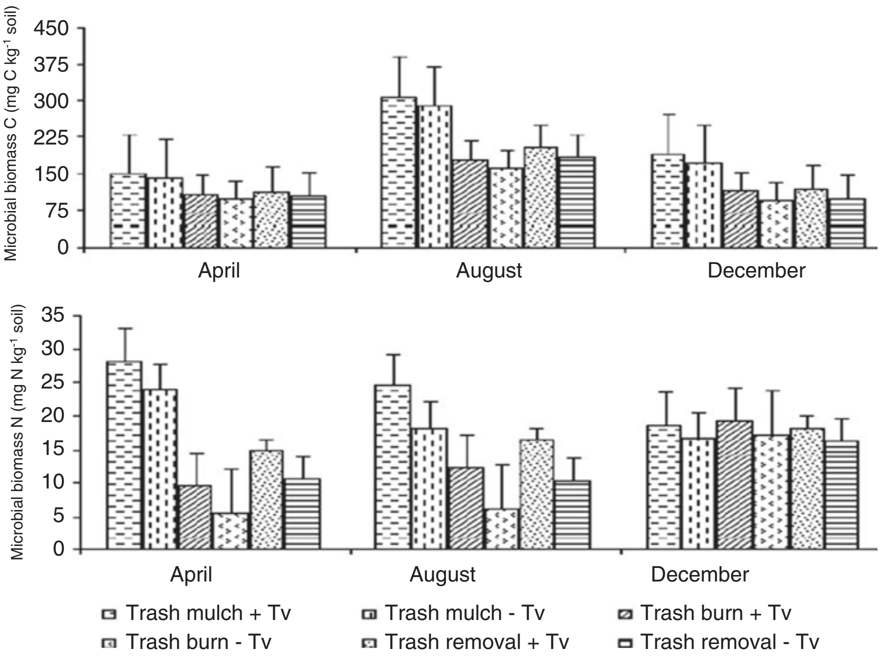

Fig. 8.2 Effect of different trash management practice with and without *Trichoderma* inoculation on SMBC and SMBN in ratoon sugarcane

Degradable crop residue cover favoured the growth of soil microflora activities, and inoculation of *Trichoderma* further enhanced the crop residue degradation. Reduction in soil microbial biomass carbon SMBC and soil microbial biomass nitrogen (SMBN) was observed in trash burning plots compared to other trash management treatments, which might be due to heat generated during burning probably affected microflora of the top soil. The increase in SMBC in August probably was due to the presence of more photosynthate and nutrients in the sugarcane rhizosphere as the crop was in its maximum growth phase and thus could release rich root exudates. SMBN at harvest declined in all plots compared to initial values. The maximum decline (13.3 mg N/kg soil), however, was recorded in plots receiving trash mulch with *Trichoderma* (Fig. 8.2). Probably, gradual decline in SMBN observed in trash mulch treatment was mainly due to the fact that initially, values were higher due to N immobilization during degradation of trash. The released microbial N could be a source for the growing crop. In case of trash burning, the initial SMBN was very low, but as the crop growth progressed with increase in the microbial activity, SMBN also started increasing as observed in the plots where trash was removed.

Mulching of soil with available plant materials protects soil from direct impact of raindrop and reducing the sediment carried with runoff (Yadav et al. 2011). It reduces soil loss up to 43 times as compared to bare soil and 17 times to cropped

Table 8.13 Effect of moisture conservation practices on total water use, water use efficiency, seed yield and net returns (mean of 2005–2016 and 2006–2007)

Moisture conservation practices	Total water use (mm)	WUE (kg seed/ha mm)	Seed yield (kg/ha)	Net returns (Rs/ha)
Control	187.0	5.05	9.48	13,262
Dust mulch (created by weeding and hoeing at 20 and 30 DAS)	184.7	6.41	11.85	17,142
Organic residue mulch (4 t/ha)	180.6	7.60	13.69	21,138

Source: Yadav et al. (2011)

Table 8.14 Effect of mulch rate on water transmission properties of an alfisol

Mulch rate (Mg/ha)	Soil water sorptivity	Soil water transmissivity	Saturated hydraulic conductivity (cm/h)[a]
0	0.32	5.56	30a
2	0.57	7.81	45a
4	0.67	7.50	70b
6	0.84	10.21	132c
12	1.05	15.36	129c

Source: Lal (1987a, b)

[a]Column values followed by the same letter are not significantly different at the 5% level (Duncan's multiple range test)

soil without using mulches. It also facilitates rainwater absorption by soil. Surface mulching immediately after sowing reduces runoff and soil loss effectively on cultivated sloping lands. Dry soil mulch to be created simply by stirring the soil with intercultural implements, minimize the evaporation from soil surface. Vertical mulching also reduces soil loss particularly in vertisols by increasing infiltration. A study conducted at Kanpur, India revealed that application of organic residues as mulch at 4 t/ha between the rows after 30 days of sowing increased significantly water use efficiency, seed yield and net returns of mustard over other moisture conservation practices (Table 8.13).

Mulching with organic materials improves the infiltration rate because it serves as a barrier for runoff, which provides more opportunity time for water to infiltrate into the profile. Mulch intercepts the rainwater and protects the soil from its biting action and checks splashing of the soil (Table 8.14). It prevents the crust formation due to clogging of soil pores, which increases infiltration rate. Furthermore, organic mulches improve the macroporosity and stability of the structural aggregates of soil and thereby improve the water transmission properties (Lal 1987a, b), which facilitate better infiltration and recharge of the soil profile. Straw mulch application increases soil water storage and storage efficiency.

The amount of water storage in the soil profile, the storage efficiency, total water use and water use efficiencies of dryland crops increase with increase in the mulch rate (Unger 1990). The increase in infiltration that results from mulch is found to be more important in some situations than its effect on reduction in evaporation for conservation of water in the profile (Table 8.15).

Table 8.15 Effect of straw mulch on soil water storage during fallow[a], water storage efficiency and dryland grain sorghum yield in Bushland, Texas

Mulch rate (Mg/ha)	Water storage (mm)	Storage efficiency (%)[b]	Grain yield (Mg/ha)	Total water use (mm)	Water use efficiency (kg/m³)
0	72c	22.6c	1.78c	320	0.56
1	99b	31.1b	2.41b	330	0.73
2	100b	31.4b	2.60b	353	0.74
4	116b	36.5b	2.98b	357	0.84
8	139a	43.7a	3.68a	365	1.01
12	147a	46.2a	3.99a	347	1.15

Source: Unger (1990)
Column values followed by the same letter are not significantly different at 5% level (Duncan's multiple range test)
[a]Fallow duration 10–11 months
[b]Precipitation averaged 318 mm

8.6.3 Crop Residue Management

Continuous decline in soil organic matter (SOM) content of soil is due to limited/reduced return of organic biomass and is identified as one of the key factors for unsustainability of the system. Burning of crop residue after harvesting without in-situ recycling (Jat et al. 2004) not only leads to loss of considerable amount of N, P, K and S but also contributes to the global NO_2 and CO_2 budget and destruction of beneficial microflora of the soil as a substantial quantum (80.12 m t per annum) of crop residues is available (Pal et al. 2002) for recycling in rice-wheat system.

8.7 Crop Rotation

Crop rotation is an agricultural management tool with ancient origins. The rotation of different nature of crops with different rooting patterns combined with minimal soil disturbance in zero-till systems promotes a more extensive network of root channels and macropores in the soil. This helps in water infiltration to deeper depths. Because rotations increase microbial diversity, the risk of pests and disease outbreaks from pathogenic organisms is reduced, since the biological diversity helps keep pathogenic organisms in check. Crop diversification, in which lowland rice is grown in rotation with upland crops including legumes, has the potential to sustain the system productivity and to alleviate the soil related health constraints. Moreover, such need-based crop diversification would fulfill the basic needs of farmers through cereals, pulses, oilseeds and vegetables, and regulate farm income by better withstanding weather aberrations, controlling price fluctuations, ensuring a balanced food supply, conserving natural resources, reducing chemical fertilizer and pesticide loads, ensuring environmental safety and creating employment opportunities (Gill and Ahlawat 2006). In the era of a shrinking land resource base, enhancing the

Table 8.16 Rice equivalent yield (REY) and sustainable yield index (SYI), available N, P, K and organic carbon contents of soil under various rice-based cropping systems

Treatments	System productivity (REY t/ha)	SYI	Available nutrients (kg/ha)			OC (%)
			N	P	K	
Rice-wheat-fallow	7.85	0.27	232.21	30.92	156.49	0.66
Rice-wheat-greengram	12.45	0.45	257.24	35.34	138.52	0.69
Rice-sorghum-greengram	9.43	0.34	264.76	34.23	143.62	0.72
Rice-castor	9.72	0.35	220.45	30.41	140.21	0.66
Rice-mustard-greengram	12.79	0.47	248.36	36.04	144.52	0.71
Rice-sorghum-groundnut	10.21	0.37	261.42	38.08	150.06	0.74
Rice-chickpea-cowpea	11.18	0.40	242.62	32.61	155.45	0.67
Rice-fenugreek-okra	25.73	0.97	251.62	31.55	153.45	0.70
Rice-onion-cowpea	24.15	0.91	236.42	37.52	161.18	0.67
Rice-chickpea-sesamum	10.28	0.37	226.45	36.90	158.24	0.66
Initial soil test values	–	–	213.0	41.30	363.23	0.65
SEM±	0.45	0.02	2.08	0.87	1.48	0.02
CD at (0.05)	1.29	0.06	6.20	2.61	4.44	0.07

The soil samples were collected after completion of three cycles of the various systems (Jat et al. 2012)

use efficiency of water and energy is important for the suitability of any cropping system. Rice equivalent yield was highest (25.73 and 24.15 t/ha) under the rice-fenugreek-okra and rice-onion-cowpea sequence compared with other sequences (Table 8.16). Cropping sequences that included legumes performed fairly well with regard to rice productivity. Reports from various parts of India indicate that the inclusion of legumes in rice-based system increased the productivity of rice (Hegde 1992). Introduction of a legume crop in the rice-based cropping system may have advantages well beyond the N addition through biological nitrogen fixation including nutrient recycling from deeper soil layers, minimize soil compaction, organic matter inputs to soil, breakup of the weed and pest life cycles and minimize the possible harmful allelopathic effects (Sanford and Hairston 1984; Wani et al. 1995).

8.8 Agroforestry and Soil Health

The integrated approach associated with agroforestry makes it the most self-sustaining and ecologically sound land management system (Singh et al. 1997). In agroforestry trees, crops and animals are integrated in a long-term conservative, sustainable, productive and eco-friendly system where greater emphasis is placed on perennial MPTs (Multi-Purpose Trees) that are planted once but yield benefits over a long period of time (Dhyani et al. 2007, 2011; Palsaniya et al. 2010, 2013). Agroforestry land use is recommended by scientists and planners for sustainable agricultural production (Nair 1984; Kang and Wilson 1987; Singh et al. 1998; Anonymous 2000; Dhyani et al. 2007, 2011), natural resource conservation (Palsaniya et al. 2011a, 2012a, b) problems soil management (Singh et al. 1989a, b, 1997; Singh 1995; Palsaniya et al. 2011a, b) and recently for mitigation of climate change by the way of sequestering carbon in both standing biomass and soil (Dhyani et al. 2013; Ajit et al. 2013; Palsaniya et al. 2011a, b).

8.8.1 Natural Resource Conservation

Agroforestry practices help in soil, water, nutrients and biodiversity conservation (Palsaniya et al. 2011a, b; Pandey 2007; Dhyani et al. 2005; Grewal 1993). Reduced runoff and soil loss and increased soil fertility due to agroforestry were observed as compared to agriculture or cultivated fallow in different agro-climatic conditions. The natural resource conservation due to agroforestry is more pronounced under fragile agro-ecosystems. Some such regional examples of agroforestry systems in India are enumerated in Table 8.17.

Table 8.17 Regional examples of effect of agroforestry systems on soil health

Region	Challenges	Changes observed due to agroforestry	Reference
Western Himalayas	Minimizing soil and water erosion in agro-ecosystems on steep slopes	Contour tree rows (hedge rows) reduced runoff and soil loss by 40 and 48%, respectively	Narain et al. (1997)
Sikkim Himalayas	Enhancing litter production and soil nutrient dynamics	N-fixing trees increased N and P cycling through enhanced litter production, resulted in greater availability of N and P, maintained soil organic matter, higher N mineralization	Sharma et al. (1996a, b)
Himalayas	Rehabilitation of degraded, abandoned agricultural and mine spoiled sites	Enhanced biomass accumulation (3.9 t/ha), soil physico-chemical properties, C-sequestration	Maikhuri et al. (2000)
Kurukshetra Himalayas	Problem soil improvement	Increased soil microbial and tree biomass, available N	Kaur et al. (2002)
Western India (Karnal)	Soil fertility improvement of moderately alkaline soils	Soil microbial biomass C increased (109.12–96.14 gg^{-1} soil) under tree plantation; soil carbon increased by 11–52% due to integration of trees and crops	Kaur et al. (2000)
Central India	Soil improvement	Soil organic C, mineral N and P increased	Pandey et al. (2000)

Singh (1988) recorded 98% reduction in soil loss under agri-horti-silvipastoral system in North Eastern Hill Region. He found *Alnus nepalensis* + pine apple + *Panicum maximum* or *Setaria sphacelata* + *Stylosanthes guianensis* in 1:1 ratio as the sustainable practice in soils having 30–60% slope. In Sivaliks where mean annual rainfall ranges between 800 and 1500 mm, due to different agroforestry system, it was observed that average soil losses with runoff water were very less as compared to agricultural systems (Grewal 1993). Similarly, Yadava and Varshney (1997) reported that a three tier silvipastoral system comprising *Leucaena leucocephala* (top canopy), *D. cinerea* (middle canopy) and *C. ciliaris* + *S. hamata* (lower canopy) reduced the soil loss by 11 times compared to bare land. It also reduced total soluble salts, dissolved N and K by 69, 67 and 43%, respectively, while organic carbon, available N and P improved by 53, 23 and 8%, respectively, against their initial status. Silvipasture along with staggered contour trenching in Kangra watershed reduced soil erosion and improved productivity, survival of plants and biomass production (Srivastava et al. 2003). Treatment with staggered contour trenching at 1 m vertical interval trapped 37 t/ha/ year silt in the watershed.

Agroforestry practices, especially silvipastoral systems along with mechanical measures are also reported to be effective checking and rehabilitating problems soils, landslides, mine spoils and torrents (Singh 1995; Singh et al. 1997; Sastry et al. 1981; Dadhwal and Katiyar 1996). A landslide site in Uttarakhand Himalaya was successfully stabilized and rehabilitated within 10 years by bio-engineering measures including plantation of *Ipomoea carnea*, *Vitex negundo* and napier grass with *Erythrina suberosa*, *D. sissoo* and *A. catechu* (Sastry et al. 1981). The above treatments reduced sediment load (320–5.5 t/ha/year), increased vegetation cover (5–95%) and dry weather flow (100–250 days). Similarly, Dadhwal and Katiyar (1996) also reported increased vegetation cover (10–80%) and decreased debris flow due to different biological measures (trees, shrubs and grasses) in mine spoiled area. Hazra and Singh (1994) reported that soil and water conservation treatments along with agroforestry helped in reducing soil loss from 41 to 9.5 t/ha from barren hillocks and from 20.5 to 5.5 t/ha from wastelands.

8.8.2 Nutrient Recycling

Agroforestry land use is known for more efficient nutrient recycling than cropping alone (Singh et al. 1996; Kumar 2007; Palsaniya et al. 2009; Yadav et al. 2009; Palsaniya et al. 2012c; Palsaniya et al. 2013). There exists nearly closed nutrient cycles in forest ecosystems where nutrient inputs from atmospheric deposition, biological nitrogen fixation, litter fall, plant residue decay and weathering of primary soil minerals are in balance with nutrient losses due to leaching, denitrification, runoff, erosion and plant removal. On the other hand, there is a net removal of nutrients from the soil via crop harvests in agricultural systems which can result in net negative balances if nutrients are not replaced through external inputs like manures and fertilizers. Inclusion of trees in agricultural land-scape can add N in soil through biological nitrogen fixation (BNF) and deep nutrient capture and recycling. The presence of active nodules in roots of leguminous species indicates that BNF can supply considerable nitrogen inputs to crops via litter in soils. The non-fixing trees such as *Cassia* accumulate more nitrogen in their leaves than nitrogen-fixing legumes, probably because of their larger root volume and nutrient capturing ability (Garrity and Mercado 1994) which can be added to the soil as green leaf manuring. *Gliricidia* and *Sesbania* are also known for their nitrogen fixation and green manuring potential. In plants like *Leucaena* the annual above ground litter N content was high (256 kg/ha) with an annual release of 208 kg/ha (Sandhu et al. 1990). Deep nutrient capture by tree roots at depths where crop roots are not present is considered as an additional nutrient input in agroforestry systems because such nutrients are otherwise leached as far as the crop is concerned. They become an input on being transferred to the soil via tree litter decomposition (Yadav et al. 2009).

Agroforestry can partially provide the nitrogen requirement of crops. Generally 20% of the N released from litter fall or pruned material is taken by the current crop (Palm 1995; Giller and Cadisch 1995) and remaining is incorporated into soil organic matter (SOM) (Haggar et al. 1993). Because of the slow release of N and P from SOM, organic inputs have a greater residual effect on soil fertility than inorganic fertilizers. The rate of decomposition is mainly regulated by edaphic, climatic variables and resource quality (Singh et al. 1989a, b, 1996; Yadav et al. 2008). Organic inputs with high N, low lignin and polyphenol will release nutrients rapidly while those with low N and high polyphenol and lignin will release nutrients slowly or even immobilize (Palm 1995). This has practical implications for attaining synchrony between nutrient release and crop nutrient demand and, hence, for efficiency of nutrient use. Maharudrappa et al. (1999) reported that incubation of litter of different MPTs enhanced nutrient availability. The available N decreased slightly at 30 days of incubation compared to control. However, available N increased at the end of 60 days of incubation. This indicated temporary immobilization of nutrients by microorganisms. Legumes constitute the cheapest source of protein to man and animals, enhance soil quality by adding organic matter and improve soil structure and water infiltration (Palsaniya and Ahlawat 2007). They act as nurse crop and supply nitrogen to the associated crops and thereby, contribute to the conservation of energy by reducing the need for N fertilization (Palsaniya and Ahlawat 2009). Therefore, introduction of suitable legumes in rangelands, pastures, silvipastures and agroforestry has great significance. Unlike N, the release of P to the available pool from litter was recorded at 30 days of incubation. Mineralization of organic matter played a major role in P release for plant growth. The decomposition of litter material with narrower C:P ratio is likely to increase the available P as compared to those with higher C:P ratio. Incubation of litter also increased available K in all the treatments. The release of K to soil was more dependent on the quantity and quality of the litter. The increase in available K may be attributed to the fact that K is not strongly bound in organic structures, unlike that of N and P.

8.9 Limitations

A mental change of farmers, technicians, extensionists and researchers away from soil degrading tillage operations towards sustainable production systems like no-tillage is necessary to obtain changes in attitudes of farmers (Derpsch et al. 2010). It is argued that convincing the farmers that successful cultivation is possible even with reduced tillage or without tillage is a major hurdle in promoting CA on a large scale. In many cases, it may be difficult to convince the farmers of potential benefits of CA beyond its potential to reduce production costs, mainly by tillage reductions. CA is now considered a route to sustainable agriculture. Spread of conservation agriculture, therefore, will call for scientific research linked with development efforts. The following are a few important constraints which impede broad scale adoption of CA.

- Lack of appropriate seeders especially for small and medium scale farmers: Although significant efforts have been made in developing and promoting machinery for seeding wheat in no till systems, successful adoption will call for accelerated effort in developing, standardizing and promoting quality machinery aimed at a range of crop and cropping sequences. These would include the development of permanent bed and furrow planting systems and harvest operations to manage crop residues.
- The widespread use of crop residues for livestock feed and fuel: Specially under rainfed situations, farmers face a scarcity of crop residues due to less biomass production of different crops. There is competition between CA practice and livestock feeding for crop residue. This is a major constraint for promotion of CA under rainfed situations.
- Burning of crop residues: For timely sowing of the next crop and without machinery for sowing under CA systems, farmers prefer to sow the crop in time by burning the residue. This has become a common feature in the rice-wheat system in north India. This creates environmental problems for the region.
- Lack of knowledge about the potential of CA to agriculture leaders, extension agents and farmers: This implies that the whole range of practices in conservation agriculture, including planting and harvesting, water and nutrient management, diseases and pest control, etc., need to be evolved, evaluated and matched in the context of new systems.
- Skilled and scientific manpower: Managing conservation agriculture systems will call for enhanced capacity of scientists to address problems from a systems perspective and to be able to work in close partnerships with farmers and other stakeholders. Strengthened knowledge and information sharing mechanisms are needed.

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9 Sustainable Management of Soil Phosphorus in a Changing World

Mina Karamesouti and Dionisios Gasparatos

Abstract

Phosphorus (P) is an important nutrient for flora and fauna, and is an essential element during energy transformation processes of the living world. Phosphate rock, which is the most common source of phosphorus, is globally used in various forms, in order to boost agricultural productivity and cover contemporary food demand. Its low price in combination with its abundance on several areas on our planet led to overexploitation phenomena and unsustainable phosphorus management, resulting in important environmental and socio-economic problems. Eutrophication, soil over-accumulation, nutrient depletion due to soil erosion processes, contamination of the extraction sites, reduction of global available resources, massive price fluctuations and food crisis are some of these phosphorus-related problems with a global impact. The uncertainties and the underlying risks prevailing due to improper use of phosphate resources denote that sustainable soil phosphorus management should be set amongst the top priorities in global level. The local adaptation of the 4R Nutrient Stewardship approach can be proved a very promising tool in order to develop a sound soil phosphorus management program. In Europe, despite the multi-dimensional problems caused by unsustainable phosphorus use of the previous decades, significant steps are taken to restore the problems and establish a framework focusing on natural resources and socio-economic system protection.

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9.1 Introduction

Phosphorus (P) is a naturally occurring element that can be found in the earth's crust, water, and all living organisms. Primarily phosphorus is available in a few minerals, the main of which is apatite. Weathering of the apatite parent rocks releases P, which can be partially incorporated into the plant tissue and be transformed into an organic form (Filippelli 2008). However, the low concentration (100–3000 mg P kg^{-1}) and its low solubility (<0.01 mg P L^{-1}) in soils make phosphorus a critical nutrient for the plant growth. Phosphorus is categorized among the 16 elements that are essential for flora and fauna growth and evolution (Mullins 2009).

In plants, phosphorus regulates a number of physiological functions such as photosynthesis, respiration, energy storage and transfer, cell division, cell enlargement, and seed formation. It is a component of many cell constituents and plays a major role in energy transformation procedures. Adequate phosphorus is needed for root growth and plant ripening. Indicatively, a Pinus tree needs to uptake approximately 10 kg ha^{-1} phosphorus annually in order to develop a high leaf area index and reach a maximum volume production (Fox et al. 2011). Phosphorus is an integral component of the adenosine diphosphate (ADP) and the adenosine triphosphate (ATP). Both ADP and ATP are fundamental organic compounds for the metabolic processes and the energy flow in living cells. In the majority of plants, P concentrations vary from 0.1 to 0.4% (Ott and Rechberger 2012). Phosphorus is also necessary for the proper growth of livestock and it is an essential component for skeleton and teeth formation. Animals cover their phosphorus needs primarily from plant products.

In traditional agricultural societies, phosphorus needs were covered by naturally available soil phosphorus and organic matter. Human excreta, along with bones, industrial organic by-products, animal dung, fish, ash and other domestic organic by-products, were common supplements that led to the improvement of local primary productivity (Cordell et al. 2009). However, during the twentieth century, due to the global increase in food requirements, the changes in dietary habits, and the uneven and limited spatial phosphorus availability, the fertilizers became the main source of the nutrient in agricultural areas (Cordell et al. 2009; Tóth et al. 2014). Indeed, it is believed that the huge population numbers in the big cities of current industrialized countries would not have been maintained if it had not been for phosphorus (Dawson and Hilton 2011; Heckenmüller et al. 2014).

Significant phosphorus exports from countries rich in phosphate rock reserves cover global phosphorus soil deficiencies. The processed mineral fertilizers, such as the Ordinary Superphosphate (OSP), became very popular since they contain significantly higher phosphorus concentrations compared to the traditional fertilizers (Cordell et al. 2009). In 2013, more than 300,000 product tones in the global fertilizer trade flows were reported (ICIS-IFA 2015). The major phosphorus exporters are Africa and West Asia, with a share of 53.6% and 27.7%, respectively, in the global phosphorus trade (de Ridder et al. 2012). During 2011, only Africa exported 15.3 Mt of phosphate rock (Heckenmüller et al. 2014; IFA 2013). It is notable that the world's phosphate resources are mainly controlled by China, the USA, Russia, and Morocco (Cordell 2008). In the period 2005 – 2015, based on FAO's reports, the global annual P_2O_5 demand has increased from 27.5 to 43.8 million tons (FAO 2005, 2012, 2015), and due to the global population increase it is expected that phosphorus demand will maintain its increasing trend. However, there is arising awareness concerning the quantity as well as the quality of the remaining phosphorus reserves. The extreme price fluctuations during the period 2007–2008 arose vivid dispute on whether and when the phosphate production will reach a peak (Heckenmüller et al. 2014).

The theoretical and practical aspects of soil phosphorus management, in this changing global framework, are going to be developed in the current chapter. The contemporary phosphorus-related challenges will be analyzed in the Sect. 9.2. Section 9.3 briefly presents the phosphorus dynamics in soils and the main prevailing environmental issues. Section 9.4 discusses the prevailing management strategies in order to meet the contemporary P-related issues. The analysis focuses in three main pillars, namely recovery of soil legacy (or residual) phosphorus, soil erosion prevention, and fertilizer recommendations. In the last section case studies and their outcomes from countries in the European Union are presented.

9.2 Phosphorus Challenges

Prodigious changes in agricultural management practices, including the extensive use of phosphorus supplements, have significantly increased food production. However, global phosphate rock exploitation faces significant challenges. Phosphorus plays a critical role in the ecosystem and since it was a highly abundant element on Earth, overexploitation phenomena, especially in developed countries, rendered phosphorus a finite resource. Moreover, phosphorus has a significantly uneven spatial distribution on Earth, with only few countries being the main phosphorus resources managers. Finally, its low price in combination with its abundance led to an unprecedented inefficient and unsustainable use, causing environmental, and socio-economic issues.

The great dependence of our lives on phosphorus is related to variable factors. First of all, the alimentation needs of our changing societies could not have been addressed without the use of mineral phosphorus. It is an irreplaceable and fundamental element for organic life since it is integral component of the RNA, the DNA, the cells, and the animal skeletons (Elser 2012). The changes in alimentation preferences and the increased meat consumption impose pressures to phosphorus demand as well. Only in China, the animal-based food consumption has increased from 61 g/ca/day in 1982 to 160 g/ca/day in 2002 (Qiao et al. 2011), increasing the necessary phosphorus quantities inside the food chain. Moreover, land degradation processes affecting agricultural land render more and more areas less fertile and poorer in naturally available vital nutrients for plants. Agricultural production in areas such as sub-Sahara and Ethiopia becomes significantly dependent on phosphate fertilization since they are already highlighted as hot spots for soil nutrient depletion (Weikard and Seyhan 2009).

Statistics provided by FAO can clearly show the increasing trend in phosphorus demand. In 2005 a 27.5 Mt of P_2O_5 demand was reported, which is expected to reach 46.6 Mt by 2018 (FAO 2005, 2015). The expected increase in P_2O_5 demand for the period 2014–2018 is estimated to be about 3.9 Mt, 58% of which is attributed to the increasing needs in Asia (with greater consumers India, China, Indonesia, Pakistan, Iran, Russia, Ukraine, and Bangladesh), 29% in America (with greater consumers Brazil, Argentina, and the USA), 9% in Europe, 4% in Africa, and 0.5% in Oceania (FAO 2015).

Although world's food production is so dependent on phosphate fertilizers, the estimation of the global phosphate reserves is a very complicated process. In 2009, Cordell et al., based on the estimated remaining global phosphate rock reserves by Jasinski (2013), calculated that the peak of global phosphorus production could be reached by 2033 (3240 Mt P). However, recent studies estimated global phosphate rock deposits ranging between 290 and 460 Gt (Jasinski 2013; Van Kauwenbergh 2010). The optimists expect that future studies will reveal greater amounts of phosphorus reserves that could support a steady productivity for more than 300 years (Heckenmüller et al. 2014). Nevertheless, the uncertainty for resources availability as well as for their quality and the economical accessibility will be a constant threat on food security and farmers' prosperity (Cordell et al. 2012; ECSCU 2013).

Currently, more than 30 countries extract phosphate rock, however, only 12 countries contribute to 95% of the global extracted quantity. Indicatively, in 2014 the leading phosphate-producing country was China (100 Mt), followed by Morocco and Western Sahara (30 Mt), the USA (27.1 Mt), Russia (10 Mt), and Brazil (6.75 Mt) (USGS 2015). The limited number of dominant phosphate-producers may have significant global socio-economic impacts, such as the most recent massive price fluctuations during 2007–2008, which skyrocketed prices for more than 900% (Heckenmüller et al. 2014). Export controls by the phosphate-producing countries is another challenge related to phosphorus global trade, which can cause technical shortages in the global markets. Characteristic was the case of China in 2008, which imposed more than 130% tariff in exports, in order to protect domestic supplies (de Ridder et al. 2012).

At the same time, highly inefficient use of phosphorus throughout the food systems was reported (Baccini and Brunner 1991). In the developed countries excessive fertilization was applied in an attempt to achieve the highest possible productivity. Historically, phosphate over-fertilization was relatively common in Western Europe and North America (Scholz et al. 2013; Syers et al. 2008), followed by significant environmental problems such as water pollution and soil over-accumulation. Eutrophication of fresh waters was the first alarming issue related to over-fertilization with phosphorus. The phenomenon refers to the natural aging of aquatic ecosystem, and has a long-lasting impact on the affected areas (Filippelli 2008; Mullins 2009). The phosphorus over-accumulation refers to the high concentrations of insoluble phosphates in agricultural soils, which are, however, not available to plants. The average annual phosphorus accumulation, for example, in the agricultural soils of the EU-27 and EU-15, was estimated between 4.9 and 8.7 kg/ha accordingly, with significant variations among the Member States (Ott and Rechberger 2012; Tunney et al. 2003; van Dijk et al. 2016).

These concerns have led governments and international organizations to formulate strategies in order to promote phosphorus's sustainable use (de Ridder et al. 2012; Sharpley et al. 2003). However, addressing the phosphorus challenges requires a multi-dimensional approach including environmental, socio-economic, geopolitical as well as technical aspects.

9.3 Soil Phosphorus: Agronomic or Environmental Issue?

Two major global problems related to soil phosphorus (P) are the limited plant productivity and the land degradation, caused by its low availability and high fixation in soils. On the contrary due to high doses of P fertilization, mostly in developed countries, phosphorus accumulation took place in the past decades with serious impact on the environment. Nowadays, phosphorus losses to surface waters and accelerated eutrophication become a serious problem. According to Delgado and Scalenghe (2008), non-sustainable management practices have caused soil phosphorus to become an environmental rather than an agronomic issue in more economically developed countries.

Historically, crop production did rely on natural sources of soil phosphorus like guano, human excreta, and manure. However, with increasing demand of agricultural production, application of phosphorus fertilizers manufactured from phosphate rock became the major source of soil P (Fig. 9.1). Phosphorus surpluses and over-fertilization have been identified for excessive phosphorus accumulation in soils, with consequent increased potential for phosphorus loss in water bodies (Hooda et al. 2001).

Despite the environmental implications, phosphorus has received only limited attention and the scientific literature in the twentieth century has paid more attention to N and C rather than to P (Delgado and Scalenghe 2008). Better insight is needed into the best management practices taking into account not only an accurate P supply to crops and food production, but also a decrease in P inputs to the aquatic environment or losses in food waste.

9.3.1 Phosphorus Dynamics in Soil

The chemistry of phosphorus in the soil is very complex since the phosphorus interaction with soil components determines the nature of the different forms of phosphorus found in soils. These chemical forms represent the two major pools of soil

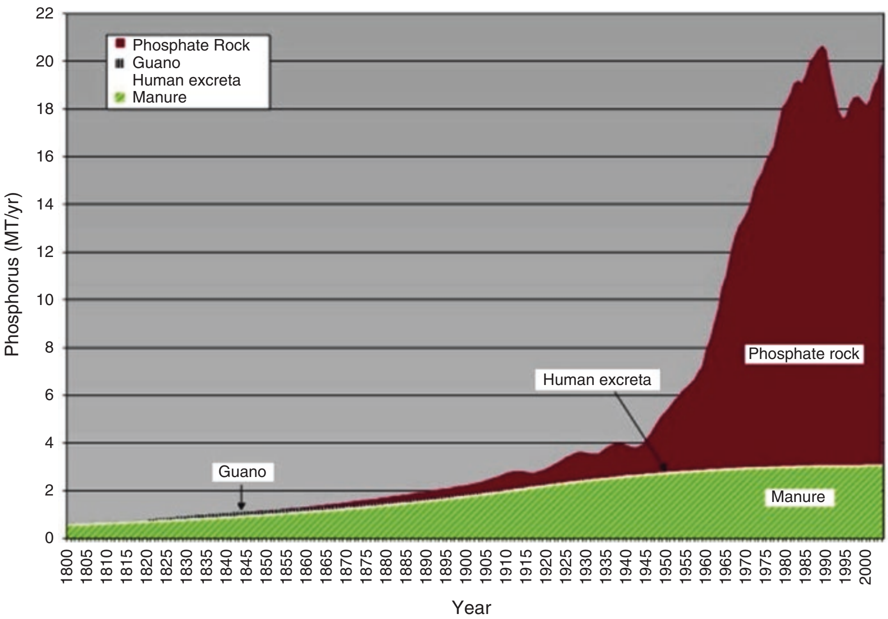

Fig. 9.1 Historical global sources of phosphorus fertilizers (1800–2000) (Cordell et al. 2009)

P; inorganic P (Pi) and organic P (Po) which differ significantly in their behavior and fate in soils. Both inorganic and organic forms of phosphorus are important to plants as sources of nutrients. The relative amounts in the two forms vary greatly among soil types but the organic P generally constitutes 20–80% of the total P in soils.

Most inorganic-phosphorus forms in soils fall into one of two categories varying in their dissolution rates: (1) those containing calcium, and (2) those containing iron and aluminum. With decreasing soil pH, the calcium phosphate compounds become more soluble and almost disappear, especially from very acid soils. On the other hand, with increasing soil pH, solubility of Fe and Al phosphates increases, while the calcium phosphates are quite stable and very insoluble (Brady and Weil 2008).

Inorganic-phosphorus reactions in soils are mainly governed by adsorption on sorbent surfaces (Al/Fe oxides) and precipitation processes (Ca phosphates or Fe and Al phosphates), depending on soil reaction (Delgado and Scalenghe 2008). In acidic soils, phosphorus can be absorbed by Fe and Al oxides and hydroxides with fast and reversible surface-based sorption reactions, forming various complexes, and slower reactions progressively resulting in subsequent occlusion of adsorbed phosphorus in nanopores that frequently occur in oxides (McLaughlin et al. 2011; Shen et al. 2011). Various Al/Fe oxides of different crystallinity such as gibbsite, hematite, goethite, ferrihydrite, as well as amorphous oxides of Fe and Al are the main components that predominantly influence phosphate sorption in different types of soils and sediments (Gasparatos et al. 2006).

In neutral to calcareous (alkaline) soils, reactions with calcium carbonate ($CaCO_3$) play a more important role in removing soluble P from soil solution (Bastounopoulou et al. 2011). Calcium carbonate can immobilize substantial amounts of phosphorus by both adsorption and precipitation of various forms of calcium phosphates. At low solution phosphorus concentrations, free $CaCO_3$ in calcareous soils can absorb phosphorous ions without precipitation of Ca phosphates, while where phosphorus concentrations are higher (e.g., around fertilizer granules) nutrient retention is dominated by precipitation reactions (McLaughlin et al. 2011). Coatings of Al/Fe oxides on $CaCO_3$ surfaces can also contribute to a large proportion on the phosphorus sorption by calcareous soils (Matar et al. 1992).

Soil Po mainly exists in organic phosphorus compounds like inositol phosphates and phosphonates, orthophosphate diesters and monoesters, nucleic acids, and phospholipids. Inositol phosphates such as phytic acid are the most abundant of the organic phosphorus compounds, making up 10–50% of the total organic phosphorus. Mineralization process (e.g., the transformation of organic P to inorganic) contributes to the plant-available P and in some cases has a dominant influence on phosphorus availability, especially in highly weathered soils. Like soil organic matter decomposition, organic phosphorus mineralization depends on soil moisture, temperature, tillage, soil pH and redox potential.

As indicated in Fig. 9.2 the dynamics of soil P is governed by many physicochemical reactions, interactions with soil components, transformations among various P pools, influencing phosphorus availability which is critical in order to improve plant productivity and agricultural sustainability (Shen et al. 2011).

9.3.2 Phosphorus Environmental Issues

The global phosphate fertilizers use is beset with variable socio-economic and environmental considerations. Despite phosphorus beneficial contribution to high agricultural productivity, significant environmental impacts occur during extraction processes, during fertilization as well as after fertilizer consumption. Naturally, phosphorus has a very slow life cycle compared to civilization time scale, however, human intensive exploitation of this nutrient has accelerated the release phase, which is accompanied by the release of several harmful substances such as heavy metals or other radioactive by-products. Other more well-known implications caused during and after fertilization processes are the phosphorus over-accumulation on agricultural soils and the water quality deterioration.

9.3.2.1 Environmental Cost of Phosphorus Industry

Environmental deterioration of the phosphate rock extraction areas is a matter of high concern. Phosphate sediments contain a plethora of hazardous elements with cadmium being the prevailing one. Cadmium concentrations in phosphate rock may be even 70-fold of the concentrations in other sedimentary formations. Indicatively, the global average cadmium levels in phosphate rock is about 21 mg Cd/kg, while in some Moroccan reserves the concentrations may exceed 40 mg (Smil 2000).

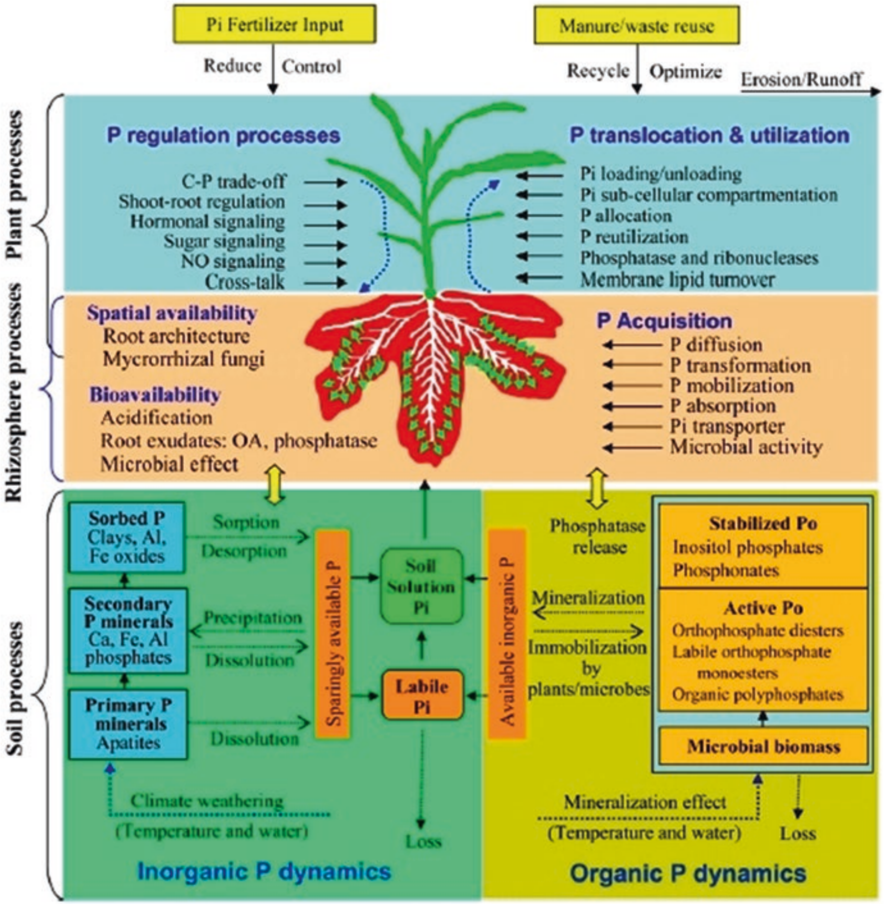

Fig. 9.2 Soil P dynamics as part of the soil/rhizosphere-plant continuum. *C-P* carbon-P, *NO* nitric oxide, *OA* organic acids (Shen et al. 2011)

Cadmium is a highly toxic element for humans, and is related to kidney malfunctions and cancer. Although the World Health Organization has set a maximum daily upper limit of 1 μg/kg/body mass, studies reveal that the European intakes are already extremely high (40 μg Cd/day per adult) (Smil 2000). The cumulative trend of cadmium on soils should be treated with caution since it can have significant impact on food chain. Besides the environmental impacts caused by cadmium, socio-economic impacts may arise as well (Ott and Rechberger 2012). Fertilizer detoxification can increase the price of the fertilizer, and consequently the price of the agricultural products, leading to a new global food crisis. Additional concerns for human health due to phosphate rock extractions derive from the radioactive enclosures. Alarming uranium concentrations in phosphorus fertilizers can be a serious threat to agricultural soils and water resources, while they can also lead to long-lasting health problems (de Ridder et al. 2012). Unless global community takes drastic measures on quantitative and qualitative control of the extracted phosphate rock, irreversible environmental issues may rise in local or global level. Soil deterioration due to contaminated fertilizers may cause even the shrinkage of valuable fertile agricultural land.

9.3.2.2 Eutrophication

Eutrophication of fresh waters was the first alarming side-effect of the over-application of phosphate fertilization. Low phosphate solubility restricts nutrient uptake by the plants, resulting in massive depletion through leaching, surface water runoff, or soil erosion processes. Since the second half of the twentieth century, phosphorus depletion in water bodies remains an issue of high concern in global agendas.

The phenomenon is related to the natural aging of aquatic ecosystem, and has long-lasting impact on the affected areas (Filippelli 2008; Mullins 2009). In affected areas, an excessive growth of flora and fauna, followed by oxygen shortages is noted. Under the absence of oxygen, organisms inside these aquatic ecosystems are condemned to death. Eutrophication is also associated with the bloom of cyanobacteria, which are very harmful for animal and human health. Apart from the environmental impact, eutrophication can be related to serious local socio-economic effects as in the affected areas multiple other functions (such as fishing, water consumption, and swimming) are prohibited as well.

Apart from agricultural fertilizers, urban and industrial wastes are contributing to the phenomenon as well. In the EU, a share of about 34% of the imported phosphates ends up to urban wastewater system (de Ridder et al. 2012), while the treated wastewater quantities vary considerably among the EU-Member States (from 4 to 97%) (Elser 2012). In the USA, more than 70% of wastewaters enter aquatic systems (Nyenje et al. 2010) forcing the government to invest more than US$2.2 billion in order to combat eutrophication-related problems (Dodds et al. 2008). Although EPA has made significant efforts to promote the aquatic system protection (the Watershed Protection Approach—WPA), water resources in the USA are still under considerable risk due to a combination of point sources and complex nonpoint sources.

9.3.2.3 Over-Accumulation

Continuous and long-term fertilization, without considering inherent phosphorus sources (i.e., manure or animal slurries), along with the poor knowledge over-fertilization efficiency, significantly increased phosphorus concentrations on agricultural soils after World War II. Especially in the EU, subsidies for increasing agricultural productivity, as well as the abundance and low price of phosphate fertilizers resulted in phosphorus saturation in western European countries (Delgado and Scalenghe 2008).

Mitigating over-accumulation, however, is not a simple process. The optimization of soil phosphorus management practices depends on various biological, chemical, and physical parameters. Indicatively, phosphorus reaction with iron, calcium, and aluminum producing insoluble phosphates can be mentioned. Under these formations, phosphorus is not available to plants and inevitably it will be accumulated to soil till it will be totally displaced under the impact of various factors. Bennett et al. (2001) estimated the terrestrial phosphorus fluxes during the preindustrial era, produced due to weathering ranged from 10 to 15 Tg $year^{-1}$. Currently, phosphorus releases due to weathering processes are estimated to range from 15 to 20 Tg $year^{-1}$, while mining processes are estimated to release another 18.5 Tg P/year on the soil surface. From these quantities only a limited fraction is available to the plants, while the vast majority of phosphorus is either transferred or accumulated to the soil. In arid or semi-arid areas, limited vegetation coverage, partially impaired soil structure with low organic matter content and rugged terrain suggest favorable conditions for phosphorus depletion (Delgado and Scalenghe 2008). But, while the hilly marginal agricultural areas are sources for sediments and phosphorus, in lowlands or flat regions phosphorus over-accumulation is an imminent threat for water resources. Characteristic is the example of Belgium and the Netherlands, with national phosphorus surpluses greater than 20 kg P ha^{-1} $year^{-1}$ (Chardon and Schoumans 2007), while the annual accumulation in agricultural soils in the EU-27 was 4.9 kg P/ha for 2005 (van Dijk et al. 2016).

Nutrient management plans should be open dynamic systems for all possible fertilizer sources in order to obtain the maximum fertilizer reuse, protecting water, and soil resources. Although during the last decades the EU has increased its efforts to reduce nutrient surpluses (EEA 2005), the whole EU15 Soil Agricultural system constitutes the biggest sink of phosphorus and the Mediterranean Sea was characterized a hot spot for high phosphorus loads (Ott and Rechberger 2012).

9.3.2.4 Soil Erosion: Nutrient Depletion

The naturally inherent phosphorus concentrations in soil and aquatic systems can be often subjected to imbalances due to natural processes, anthropogenic pressures, or an interaction of these factors. A significant interplay among soil, water, and human systems can be spotted in two distinct but highly correlated processes, the soil erosion and the sediment transportation. The driving force of these two natural processes is gravity, which can be enhanced by physical forces (wind, rain, glaciers, roots, and forest fires) or human activity (land use changes, intensified land management practices, deforestation, and deliberate wildfires). During soil movements, nutrients attached to soil particles or the soil organic matter participate to the translocation procedure. The phenomenon can be primarily identified in agricultural soils of marginal hilly areas. In these sites the unsaturated subsurface soil horizons with the high sorptive capacity are ideal pathways for nutrient depletion (Delgado and Scalenghe 2008). The nutrients and other chemical compounds attached to sediment particles can be translocated to long distances under the impact of heavy rainfall events, strong winds, or glaciers movements. The most common processes are soil erosion due to water circulation and tillage. The water flow washes away the soil particles and organic matter leading them into water bodies. Their destination will be the bottom of low flow rivers, lakes, or even the sea. In these areas the enriched sediments settle, while part of the attached substances can be detached and become soluble in the water. An aquatic ecosystem may change drastically after a serious storm since loads of mud reach the water reducing light penetration, causing siltation, sedimentation, and even water chemical quality deterioration (USEPA 1996). The excessive phosphorus loads following this route boost productivity, inevitably cause eutrophication, and increase the oxygen water demand in sediments and water (Niirnberg 1994). Losses of phosphorus due to erosion have been detected in a number of agricultural areas (Filippelli 2008; Quinton et al. 2010), while the problem greatly enhances under intensive land management practices (Chardon and Schoumans 2007; Filippelli 2008; Mullins 2009).

Soil characteristics (soil texture, parent material, rock fragment content) as well as fertilization methods, rate, and timing are critical factors to phosphorus loss processes. Other critical factors are the topographic characteristics (i.e., the slope gradient and the slope length) (Nearing et al. 2005), the prevailing climatic conditions (i.e., rainfall intensity and annual rainfall distribution), the vegetation cover type and density, and the land management practices (Louwagie et al. 2009; Schröder et al. 2011). Effective and sustainable solutions for the environmental problems caused by phosphorus's excessive use require multi-sector participation, including new partnerships between government, industry, research representatives from the fertilizer industry, agriculture and food processing industry, nutrition and health, sanitation sector, solid waste management industry, environmental protection agencies, and sustainable systems researchers and practitioners (http://phosphorusfutures.net/the-phosphorus-challenge/).

9.4 Sustainable Phosphorus Management Strategies for Agricultural Soils

High agricultural productivity relies on phosphate fertilizers, which became widely popular due to their low cost. The productivity of the phosphate fertilizers maintains an increasing pace which is expected to reach 50–100% by 2050 (Cordell et al. 2009). However, three major issues are correlated with the excessive fertilization of agricultural areas. The first issue that has to be addressed is the eutrophication affecting aquatic ecosystems. Another issue is the uneven terrestrial phosphate rock distribution, revealing a dipole of areas facing phosphorus over-accumulation and areas with restrictions in productivity due to major phosphorus deficiencies. Lately, an emerging issue is the assessment of the remaining global phosphorus reserves. Although phosphorus does not vanish from our planet, under specific conditions this indispensable nutrient ends up in forms that humankind cannot easily, or no more, exploit. Furthermore, due to the fact that the magnitude of natural global phosphorus cycle (10^7–10^8 years) is enormous compared to the civilization time scale (10^3 years), the nutrient was characterized as a non-renewable resource, which should be efficiently exploited, taking into consideration the rules of sustainability (Cordell et al. 2009; Smil 2000).

Globally, several efforts have been made targeting the improvement of phosphorus usage efficiency in crop fields and pastures (Schröder et al. 2011; Syers et al. 2011; McLaughlin et al. 2011; Pagani et al. 2013). Among these is the 4R approach (Right product, Right rate, Right time, Right place) by IFA (2009) and IPNI (2012), targeting the reduction of nutrient loss from agricultural areas. Apart from changes in fertilization practices, the adoption of land management practices that protect soil quality and limit soil erosion, the suitable land use planning, the nutrient recycling plant breeding as well as the use of microorganisms are some more steps that promote the sustainable use of phosphorus resources (Sharpley 2016).

9.4.1 Legacy Phosphorus: Improving the Recovery

According to Sattari et al. (2012) and Rowe et al. (2016) legacy (or residual) phosphorus is defined as

$$P_{legacy} = P_{inputs} - P_{outputs} - P_{losses}$$

where P_{legacy} = Legacy phosphorus, P_{inputs} = Phosphorus inputs to soils (fertilizers, manures), $P_{outputs}$ = Phosphorus removed by crop production, P_{losses} = Phosphorus losses (runoff and leaching), and represent the cumulative phosphorus that has accumulated in soils from continuous inputs of fertilizers and manures.

In general, only 10–20% of the applied P in the first year is taken up by crops while the remainder accumulates in the soil to extent depending by soil and crop properties as illustrated in Fig. 9.2. The very low percentage of P fertilizers utilization is the result of the unique properties of P in soil such as low solubility, low mobility, and high fixation by soil components (Fe/Al oxides, clay minerals, calcium carbonate, organic matter) (McLaughlin et al. 2011; Shen et al. 2011).

However, the misconception that P fixation is irreversible has led the farmers especially in developed countries (e.g., Western Europe) to adopt the "build maintenance fertility program" or the insurance perspective in order to maintain the available-P pool in soil well above critical values which, in fact, means feed the soil and not the crop. This approach with long history of phosphorus fertilizer use has been recorded in many countries like Australia, UK, Denmark, and China. Sattari et al. (2012) suggest global accumulation of legacy phosphorus for the last 42 years (1965–2007) averaged 550 kg P ha^{-1} amounting to 815 Tg of P.

Many long-term studies have shown that the various forms of legacy phosphorus appear to be reversible and can generally support, without the application of fresh fertilizer, adequate crop production for 10 years or more (Rowe et al. 2016 and the references therein).

Withers et al. (2014) have shown that the two main P pools in the soil—native phosphorus and legacy phosphorus—represent a dynamic continuum of P availability ranging from highly labile forms (extracted by various soil test P—STP) to moderately and non-labile forms (Fig. 9.3).

In many cases legacy P has been identified as pollutant and major source of eutrophication issues affecting water bodies (McDowell et al. 2015; Sharpley et al. 2013).

A main challenge will be to utilize the variable amounts of the legacy soil P that are available for plant uptake in such a way that optimal crop production can be achieved with minimal P losses at reduced soil P levels (Fig. 9.4).

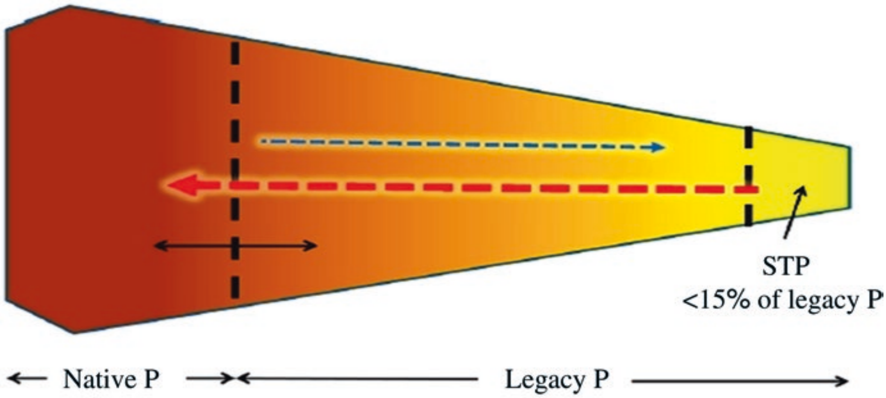

Fig. 9.3 Schematic representation of the dynamic nature of native and legacy (or residual) phosphorus. The *dotted lines* represent the sorption diffusion pathways; the dominant (*red line*) occur when highly labile soil phosphorus forms (which measured by soil phosphorus test—STP, *right*) transform to non-labile phosphorus forms (*left*) while the opposite (*blue line*) will occur if STP is allowed to decline (Withers et al. 2014)

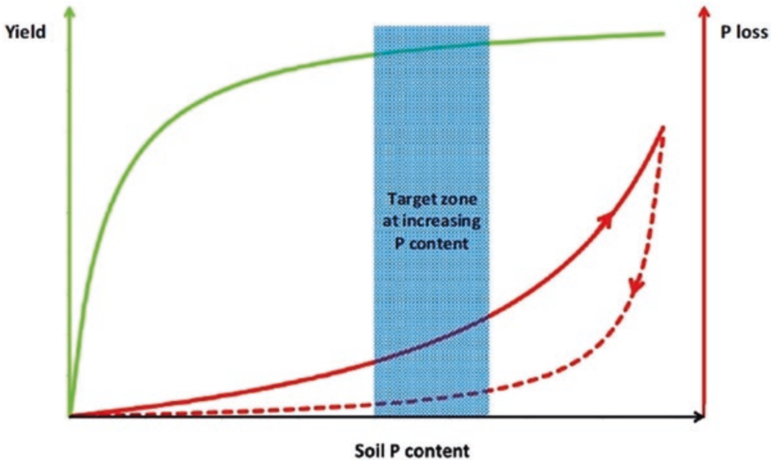

Fig. 9.4 Schematic representation of the relationship between yield and phosphorus loss at increasing soil P content (*solid lines*). *Dotted line* represents the expected P loss at decreasing soil P content due to utilization of legacy P (Schoumans et al. 2015)

Possible options for improving the mobilization of legacy soil P include multiple-level approach to managing nutrients, maintaining soil quality, and adopting more precise farming. This complex set of actions is completed with advances in breeding crop cultivars and beneficial microorganisms as crop inoculants. Although each of the following options individually might make only a small contribution to utilization of legacy soil P, the combined effect may be sufficiently exploit legacy P (Table 9.1).

Table 9.1 Strategies for improving the utilization of legacy soil P (adapted from Rowe et al. 2016; Bindraban et al. 2015; Withers et al. 2014; Shen et al. 2011)

Soil-crop management	Plant breeding	Microorganisms
Depletion of readily available phosphorus at critical levels	Root genetic traits (root elongation, branching and development of root hairs, enhancement early root growth)	*Bacillus, Pseudomonas*, and *Penicillium genera*
Maintain soil quality	Release of exudates (organic acids, carbon substrates, and enzymes)	Arbuscular mycorrhizal fungi (AMF)
Modification of soil pH	Physiological alterations (low metabolic P demand, low photosynthate needs)	Bioinoculant products
Tillage practices	Selecting crop varieties for high P—use efficiency	
Fertilizers inputs		
Crop rotation		

9.4.2 Erosion and Phosphorus: Preventing the Loss

Soil erosion (including water erosion, tillage erosion, and wind erosion) is characterized as the main phosphorus loss process especially in the marginal slopping agricultural areas, with fundamental economic, social, and environmental consequences. US Environmental Protection Agency in 1996 characterized the sediment transportation as the most common source of pollution in the agricultural watersheds, while in the Sahelian regions it is assumed that soil erosion and runoff affect 40 and 48% of the intensively cultivated highlands, respectively (Syers et al. 2011). The monoculture, the row crop cultivation, and the weed control are agricultural practices which leave the soil partially covered and exposed to extreme rainfall events (Delgado and Scalenghe 2008; Kairis et al. 2013; Tufekcioglu et al. 2013). Therefore, high P losses can potentially occur. Although the cultivated areas are principal sites for P depletion, the grazing lands have also a significant share in the process due to the limited vegetation coverage and the impaired soil structure due to compaction, while the stream banks are hot spots for phosphorus release due to soil erosion processes as well (Tufekcioglu et al. 2013; Villamil et al. 2001).

Due to poor understanding of the broader system mechanisms, estimation of global phosphorus loss caused by soil erosion often involves particular large uncertainties (Schröder et al. 2011). Soil is part of an extremely dynamic system (the Earth system), with high regional variability (i.e., regional differences in soils, climates, plants, agricultural technologies). Indicative for this variability are the average soil erosion estimates in the USA (10 ton ha^{-1} $year^{-1}$) and China (40 ton ha^{-1} $year^{-1}$) (Pimentel et al. 2010). Subsequently, a broader scientific framework focusing not only on innovative fertilization practices for phosphorus, but also on prevention/mitigation strategies such as modelling, soil quality conservation, and sustainable land management techniques could reduce environmental pressure and safeguard the long-term supply of this fundamental nutrient (Delgado and Scalenghe 2008).

9.4.2.1 Efficient Phosphorus Use and Over-Application Reduction

The low solubility of phosphorus is the limiting factor for the plant uptake. Thus any phosphorus over-application can cause soil buildup or depletion (Mullins 2009; Sharpley 1985). The excessive phosphorus loads boost productivity and consequently cause eutrophication increasing the oxygen demand in sediments and water bodies (Niirnberg 1994). Important information on phosphorus losses due to soil erosion, and consequently clues on how to prevent over-fertilization, can be extracted by the knowledge of basic soil characteristics. The percentage of phosphorus sorption on soil particles and the percentage of the nutrient that remains in a soluble form are highly related to the soil texture. Coarse textured soils or organic soils are more prone to leaching processes compared to soils with higher clay content (NRCS 2006), while soils with higher rock fragment content are less prone to erosion processes in slopping areas (Nearing et al. 2005).

So far the codes of good agricultural practices cover activities such as application periods, fertilizer usage near watercourses and on slopes, manure storage methods, crop rotation, and other land management measures. Moreover, it is suggested that that programs should include more localized regulations such as obligatory measures concerning periods of prohibition of the application of certain types of fertilizer, capacity of manure storage vessels, limitations to the application of fertilizers (on steep slopes; to water-saturated, flooded, frozen, or snow-covered ground; near water courses) (FAO 2015).

9.4.2.2 Prevention/Mitigation Strategies

Modelling

Among the most widely used technics in forecasting and prevention are models. Models help human to understand, simulate, foresee, and create scenarios for the evolution of a phenomenon. Based on their objective they can be categorized as conceptual models, process-based models, physical-based models, or dynamic process-based models. However, modelling tools cannot be considered as standalone tools, while their credibility highly depends on an accurate calibration and validation (EEA 2005; Karamesouti et al. 2016). Indicatively, the Soil Changes Under Agroforestry (SCUAF) model (Young et al. 1998) is a deterministic model that can be used to predict crop yield as a function of changes in soil carbon, nitrogen, and phosphorus content (Magcale-Macandog 2002). Other models that have been developed to describe hydrological, sediment, and phosphorus dynamics on terrestrial and/or aquatic systems include SWAT, TOPMODEL, HSPF, AGNPS, and INCA-P models (Arnold and Fohrer 2005; Borah and Bera 2004; Daniel et al. 2011; Ongley et al. 2010; Wade et al. 2002).

Soil Quality Conservation

Soil characteristics are directly related to erosion vulnerability and hence to phosphorus movements due to soil particles translocation. In agricultural areas, conservation tillage practices (a method that exploits crop residues), which are widely used for diminishing soil erosion processes, could contribute to the preservation of phosphorus resources as well (Agus et al. 2016). In pastures, sustainable stocking rates prevent extended soil compaction and accelerated soil erosion processes, which significantly contribute to nutrients depletion (Kosmas et al. 2015). Moreover, forested areas are significant phosphorus reservoirs, while the dense vegetation coverage protects soil from erosion processes and nutrient losses (Scholz et al. 2014).

Conservation Tillage

No or Minimum Tillage

Crops are directly planted into residues that have not been tilled. Minimum tillage or absence of tillage practices preserve soil structural stability and soil infiltration capacity, while they prevent temperature increase and organic matter decomposition. Water runoff and thus soil erosion processes and phosphorus translocation are reduced.

Strip Tillage

In areas with very heavy soils, minimum or no tillage is not always the best option. For these cases strip tillage proves to be a better soil management practice with significant advantages for the ground and limited soil disturbances. In flat and poorly drained soils, strip tillage enables water excesses to dry out without destroying the soil structure. Crops are directly planned into residues that have been tilled in narrow strips. Due to the maintenance of crop residues between the tilled zones, the soil is adequately protected from erosion processes, while placing fertilizer in-furrow makes the nutrients readily available for the plants. Strip tillage is a technique that conserves soil structure and valuable crop fertilizer nutrients.

Ridge Tillage

Ridge tillage involves the removal of ridge-tops into adjacent furrows, while the rest part of the field remains undisturbed. Planting is completed on the ridge and is conducted by sweeps, disk openers, coulters, or row cleaners. Weed control is accomplished with crop protection products (frequently banded) and/or cultivation. Ridges are rebuilt during row cultivation. High percentage of organic matter content is secured, preventing soil temperature increase, soil structure impairment, and nutrient loss.

Mulch Tillage

Plant residues integration in soil increases soil organic matter content, improves soil structure, scales down the raindrop impact, and hence soil erosion and nutrient loss. Mulching prevents soil temperature increase. High temperatures in soil promote microbial activity and increase carbon emissions, impacting soil aggregate stability.

Sustainable Grazing

Livestock density affects the quality of soil and water resources, while having a significant impact on the vegetation quality. Compaction and vegetation coverage reduction are some of the signs of overgrazing, followed by high soil erosion and nutrients depletion. Sustainable livestock number preserves soil infiltration capacity and soil porosity which are key factors for plant growth, soil erosion, and phosphorus depletion (Kosmas et al. 2015).

Prevent Deforestation/Reforestation

Deforestation and deliberate wildfires have a double impact on phosphorus loss processes. Firstly, nutrient depletion can be accelerated due to the increasing soil erosion processes in the affected areas. Secondly, the nutrient quantities in the flora turn into ashes, which can be easily translocated under the wind or the rainfall impact (Filippelli 2008; Louwagie et al. 2009). Hence, by protecting forests nutrients are preserved as well.

Preserve Wetlands

Wetlands are multifunctional systems since they are habitats for a plethora of living organisms, while they contribute to flood control and they can regulate shoreline erosion processes, water pollution, and nutrient depletion. Vegetation in wetlands decreases water speed providing more time for sediments and other substances to settle. Thus, plant roots can trap sediments, metabolize and detoxify pollutants, and remove nutrients before they reach open water (USEPA 1996).

Land Management Techniques

Earthworks targeting soil erosion control can contribute to the reduction of phosphorus depletion as well. All techniques have the same principal idea, which refers to the reduction of the slope length in steep hilly areas, downscaling rainwater velocity and its impact on soil.

Terracing

In agricultural areas terracing is an ancient method to expand agricultural land in slopping areas, lead water to desirable places, and properly utilize it for irrigation purposes. Although terraces provide adequate soil protection against water erosion processes, they have a significant maintenance cost. Thus they are often poorly maintained or even abandoned, facts that may have adverse effects concerning soil protection.

Contour Ploughing

Contour ploughing is a widely spread technique favorable to water and soil resources conservation. Under contour ploughing, cultivation is conducted following the natural earth forms, providing more time to the rainwater to be infiltrated in the soil. Thus, erosive effect due to rainfall along the slope length is significantly reduced, lessening soil particles transportation and consequently phosphorus losses.

Buffer Stripping

Vegetated buffer strips are used as sediment and nutrient traps, downscaling water runoff speed and increasing available infiltration time period (Scholz et al. 2014).

However, studies have revealed that under special conditions (i.e., increased phosphorus solubilization and frost) the buffering capacity of these formations can be significantly reduced (Delgado and Scalenghe 2008).

9.4.3 Phosphorus Fertilizers: Changing the Practices

In most developed countries, farmers have been following for many years a buildup and maintenance concept as the main strategy to phosphorus fertilization. However, the approach of insurance or "better safe than sorry" attitude, which supports the maintenance of optimum or higher than optimum soil test levels, has led to large phosphorus accumulation in soils over time. This increase of soil P, in excess of crop needs, poses a risk of excessive P losses from land to surface waters, changing the trophic status of water bodies (eutrophication). Recognition of agronomic issues as within-field variability in soil properties and the rapid advances on precision farming make site-specific nutrient management to gain popularity. Moreover, uncertainties and underlying risks due to the turbulences in the global phosphate rock markets highlight the sustainable and sufficient phosphorus use as a major issue. The social, economic, and environmental parameters that should be taken into consideration denote that phosphorus-related issues are very demanding problems, requiring multi-dimensional approach.

Two of the most popular approaches with multi-dimensional perspective on nutrient management are the 4R Nutrient Stewardship approach (IFA 2009; IPNI 2012) and the improved 5R strategy (Rowe et al. 2016; Withers et al. 2014). Both of them are based on Universal principles, which, however, should be well adjusted in local conditions in order to provide a desirable result (Force 2009). The 4R Nutrient Stewardship approach gives excellent recommendations on the selection of P fertilizer, by focusing on the right sources, the right rate, the right time, and the right placement (IPNI 2012) (Table 9.2).

Some of the recent studies (McLaughlin et al. 2011; Pagani et al. 2013; Schröder et al. 2011; Withers et al. 2014) focusing on sustainable phosphorus management describe basic principles targeting the four main pillars of the phosphorus 4R Nutrient Stewardship approach, which can be adjusted as follows.

9.4.3.1 Right Sources

Phosphorus in soils is not always readily available to the plants. The nutrient, in the soil and the soil solution, can be met under two main phases, the organic and the inorganic, the latter of which consists the main pool of phosphorus available to the plants. Through fertilization it is attempted an increase of the inorganic fraction, however, particular soil and fertilizer characteristics should be always taken into consideration.

In neutral and alkaline soils, soil pH reduction around fertilizer granules can trigger the reactions that release phosphorus from soil solution. Indicatively, in these soils the co-application of ammonium salts can increase the solubility and effectiveness of phosphorus fertilizers. Ammonium sulfate ($(NH4)_2SO_4$) with monocalcium

Table 9.2 4R Nutrient Stewardship approach (IFA 2009)

Right sources	Right rate	Right time	Right placement
• Supply nutrients in plant-available forms • Suit soil physical and chemical properties • Recognize interactions between nutrient elements and sources • Recognize blend compatibility • Recognize crop sensitivities to associated elements • Control effects of non-nutritive elements	• Assess soil nutrient supply • Assess all available nutrient sources • Assess plant demand • Predict fertilizer use efficiency • Consider season-to-season variability in nutrient demand • Consider nutrient budgets • Consider rate-specific economics	• Assess timing of crop uptake • Assess dynamics of soil nutrient supply • Assess nutrient release and availability from fertilizer products • Recognize timing of weather factors influencing nutrient loss • Evaluate logistics of field operations	• Recognize root-soil dynamics • Manage spatial soil variability within fields and among farms • Fit needs of tillage system • Limit potential off-field transport of nutrients

phosphate (MCP) has proved to increase the recovery of fertilizer by maize. Nevertheless, nitrification-induced pH changes affect phosphorus desorption rather than phosphorus dissolution (i.e., increase P availability without increasing the labile pool) (McLaughlin et al. 2011). In acidic soils, soil pH reduction can be achieved by the use of silicate compounds. Silicate incorporations disrupt the bonds of phosphorus with Al and Fe oxides, releasing P from the soil solution. It was found that the application of sodium silicate to an acidic sandy-clay soil reduced P sorption and increased P concentrations in maize shoots, from 0.55 to 0.91 mg/g (McLaughlin et al. 2011).

In long-term fertilized soils in the UK, there were reported higher levels of microbial phosphorus (and readily extractable P), in areas where manure was applied, compared to areas under mineral fertilization. However, phosphorus from manure should be managed very carefully since applications of manure to meet crop N needs, apply three to four times more phosphorus than annual crop needs. Therefore long-term manure applications may increase soil phosphorus above the critical level, resulting in loss of phosphorus in water bodies (Sharpley 2016).

Slow release phosphorus fertilizers are more suitable for slow growth perennial pieces, and may improve the phosphorus use efficiency in pastures with high rainfall levels and/or coarse textured soils.

Liquid fertilization is proved to be more efficient under certain soil conditions. Experiments have shown even a 15-fold greater effect of fluid fertilizers compared to granular ones (McLaughlin et al. 2011). Lombi et al. (2004) found that in calcareous soils, fluid fertilizers favored higher phosphorus diffusion compared to granular fertilizers. On the contrary, liquid fertilizer is better spread out, limiting phosphorus precipitation and consequently improving use efficiency. Currently, liquid fertilization is mainly restricted to calcareous and alkaline soils.

Other new fertilizer formulations suggest the polymer-coated, organo-mineral, and liquid products for soil application, bioinoculants, seed dressings, and foliar applications. These products reduce phosphorus fixation, trigger soil microbial activity to mobilize soil phosphorus legacy, for a more efficient plant uptake (Withers et al. 2014).

9.4.3.2 Right Rate

Efficient phosphorus use is highly dependent on plant demands and plant capability to uptake the nutrient. However, fertilization should not be conducted unless previous phosphorus imports and exports are specified. Moreover, fertilization on a routine basis, disregarding soil characteristics, increases possibilities for phosphorus over-accumulation.

Slow release of phosphorus is a technique that significantly improves nutrient uptake by the plants, while it is considered very effective in acidic soils ($pH_w < 6$) or in areas with high or very high precipitation levels (850–100 mm/year). Indicatively, studies in barley fields have shown a phosphorus uptake increase from 12.2 to 25.8%, when large single additions of phosphorus fertilization were replaced by small periodic ones.

For slow-growing perennial species and/or for areas where there is high risk for leaching processes, small periodic additions of monoammonium phosphate (MAP), diammonium phosphate (DAP) can increase fertilizer use efficiency, while magnesium ammonium phosphate and reactive rock phosphates (RPRs) also have slow release characteristics (McLaughlin et al. 2011).

9.4.3.3 Right Time

Climatic conditions and consequently soil water content play a significant role in the efficient use of phosphorus fertilizers, and soil moisture highly affects the residual phosphorus in soils (Officer et al. 2009). During the dry periods, when soil water is extremely limited, phosphorus diffusion to the rhizosphere is reduced. On the contrary, during the wet period, when soils are adequately wet, phosphorus use efficiency increases. Generally, in humid soils, the timing of phosphorus application before planting does not play a highly significant role. However, a runoff event 2 weeks after the fertilization may result to considerable losses. Consequently, the rainy periods are periods that considerable nutrient losses are expected, unless incorporation techniques are applied (i.e., subsurface banding or phosphorus injections) (Pagani et al. 2013).

Apart from the seasonal period, crop growth cycle is another time frame that should be taken into consideration when scheduling fertilization. Phosphorus shortages might be noticed in annual crops, especially during the initial stages, with the daily uptake demand per unit of root length to be relatively high, since root proliferation starts by this period (Schröder et al. 2011). Adequate phosphorus supply in early stages stimulates the photosynthetic leaf area and increases grain sink size to maximize yield and phosphorus use efficiency (Pagani et al. 2013).

9.4.3.4 Right Placement

Soil erosion, surface runoff, and leaching are the major causes of phosphorus loss from the ground. The vertical and the horizontal components of phosphorus fertilization can prove critical for the efficient use of the nutrient. Vertically, shallow fertilizer incorporation to the soil subsurface is a technique that may significantly reduce the loss. Subsurface phosphorus banding or phosphorus injections to the ground are promising fertilizer management practices during wet periods or periods with snow cover, especially in areas with frequent storm incidents and in soils with high retention capacity, such as soils with high content of aluminum and iron oxides or reactive calcium carbonate (Pagani et al. 2013). However, in the case of a sever runoff event right after the fertilization, significant losses are expected. Placing fertilizers close to the root zone area is suggested as an optimum placement practice, improving plant uptake and increasing productivity. Indicatively, studies have shown even a 3.6-fold yield increase when nutrients were incorporated into the subsoil, compared to surface fertilizer application (McLaughlin et al. 2011). However, the main drawback of subsurface banding is the difficulty to apply fertilizers into the subsoil, while banding may reduce phosphorus use efficiency in places where precipitation reactions prevail, compared to sorption reactions. Subsurface placement can improve phosphorus use efficiency in permanent pastures as well (McLaughlin et al. 2011). Horizontally, the spreading techniques such as broadcasting, with irregular, patchy spreading patterns may result in over-fertilized and nutrient deficient areas (Schröder et al. 2011).

Liquid fertilization, as previously mentioned, has proved to be an efficient placement way as well, while it has been found that placing phosphorus together with ammonium N not only increases root proliferation but also releases organic acid anions favoring legacy phosphorus mobilization (Withers et al. 2014).

9.5 The Case of European Union

The Global awareness on phosphorus fertilizer trade and use affects the European Union as well. For the vast majority of EU members, the agricultural productivity is largely dependent on phosphorus imports, since domestic resources are highly limited and mainly located in Finland. Morocco and Russia are the main phosphate rock providers of the European Union, while, France, Germany, Italy, Spain, and the UK account for over three-quarters of the Union's imports (de Ridder et al. 2012).

Norway was the leading country in the high quality phosphate rock extractions (1851), followed by the USA in the late 1860s (Smil 2000). After World War II, the need to cover alimentation needs, the poor knowledge on fertilization efficiency, the resource abundance as well as the low price led to excessive use of fertilizers. Since the 1980s, in some agricultural areas in the Netherlands, the total phosphorus concentrations in soil and aquatic systems had increased even by 90%, while in the 1990s, over-fertilization was characterized as a serious environmental threat within the European Union (Delgado and Scalenghe 2008). After the mid-twentieth century serious efforts were made by the European countries to control point sources of water pollution (industrial wastewaters purification, extended sewerage systems equipped with phosphorus and nitrate purification systems, and forbiddance of phosphorus detergents), however, water resources remained under considerable risk (Schoumans et al. 2014). In the first decade of the twenty-first century, Römer (2009) reveals that 70–80% of the agricultural soils in the European countries have so high phosphorus concentrations that satisfactory agricultural yields could be achieved without extra fertilization for several years. Latest studies reveal much more encouraging results, showing average fertilization consumption 6 kg P/ha in the European Union, when the average global consumption reaches 10 kg P/ha (van Dijk et al. 2016).

After the turbulences in the Global phosphate trade in 2007–2008, and under the threat of resources depletion, the sustainable phosphorus usage was highlighted as an overarching issue. Although the European Union was considered a region with food affluence, the aforementioned crisis revealed a significant vulnerability (Schröder et al. 2011). A great debate, dealing with alternative phosphorus management techniques, started in the European Union.

The first integrated Action was established in July 1997, under the EU COST Action 832. The principal goal of this action was the establishment of a common framework for studying phosphorus loss mechanisms among the variable phosphorus sources. The Action lasted about 5 years with 16 EU-Member States joining the project. The key subject areas included terminology, sampling and analytical procedures, principles of fertilizer and feed recommendations, inorganic and organic soil phosphorus release, erosion, leaching, incidental loss, phosphorus loss risk assessment, hydrological pathways, scaling issues, approaches to modelling phosphorus loss, and future research needs (http://www.cost832.alterra.nl/). The scientific community recognized the identification of Critical Source Areas (CSA) for phosphorus losses as a primary target. However, the process is highly demanding due to considerable heterogeneity among natural and institutional characteristics among the EU countries (Delgado and Scalenghe 2008). The acute differences in climatic conditions, natural vegetation, and geomorphology among the countries significantly diversify the problems related to phosphorus. The northern countries mainly face issues due to phosphorus over-accumulation in soils, while the southern regions tend to face mainly depletion issues (Delgado and Scalenghe 2008). Another significant issue that was disclosed was the inefficient use of fertilizers. In the EU-15, 4.7 kg P/ca/year was recorded, of which only 1.2 kg reached the consumer (van Dijk et al. 2016). Other highlighted issues were the poor nutrient recycling (0.77 kg P/ca/year), the soil over-accumulation (2.9 kg P/ca/year), and the phosphorus depletion in aquatic systems (0.55 kg P/ca/year) (van Dijk et al. 2016). Livestock diets with high phosphorus concentrations are another possible cause for local over-accumulation (Schröder et al. 2011), while degraded forested areas are potential hot spots for phosphorus depletion (through soil erosion processes) (Scholz et al. 2014).

In policy level, the most important EU environmental directives regarding the soil quality are the Nitrates Directive (91/676/EEC) and the Water Framework Directive (2000/60/EC). Through the Water Framework Directive (WFD) the EU countries are called to improve the quality of water resources till 2027. In 2006, the

European Commission published the Soil Thematic Strategy (COM 2006–231) targeting the protection and sustainable use of soil resources. The European Member States are called to identify areas with high soil resources deterioration risk and propose policies in order to address the problem (Louwagie et al. 2009).

By adopting measures targeting the reuse and recycling of phosphorus, the EU will manage to protect the natural resources and reduces the potential socio-economic impacts from turbulences in world phosphorus trade.

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Wastewater in Agriculture: Possibilities and Limitations

10

Shovik Deb and Puspendu Dutta

Abstract

Wastewater use in crop irrigation is common in urban and sub-urban areas around the world. The source may be rural house-holds, industry or municipal sewage sludge. This application of wastewater in agriculture can be a good alternative under increasing scarcity of clean water. Besides, use of wastewater may facilitate the expansion of area under irrigation and it can serve as supplementary source of nutrients. However, contamination of soil by wastewater carried pathogen and heavy metals is a concern. It can degrade soil quality, harm plants, disturb the environmental equilibrium and is hazardous to human health in a long run. Therefore, holistic monitoring and management is necessary for sustainable use of wastewater. Care should be taken regarding the proper treatment/reclamation of industrial and municipal wastes before their dumping in soil.

Keywords

Wastewater • Source of nutrient • Environmental degradation • Sustainable use

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10.1 Introduction

Water security is gaining priority in the modern world due to continuous decline in per capita source of freshwater. As per the report of United Nations (2006), about 20% of the global population are suffering from water shortage in the beginning of twenty-first century and the scenario would be much worse at 2050. This is not only the problem of arid or semiarid regions, but also countries over-consuming their water resources will face this scarcity (Coppola et al. 2004). Use of wastewater as a possible substitute of freshwater in some aspects of modern life may be a solution.

Worldwide, agriculture utilizes a lion's share of freshwater (Hoekstra and Chapagain 2007). Therefore, any alternative of freshwater in agriculture is a matter of high concern. The utilization of wastewater in crop irrigation appears as a potential theme here. Use of wastewater in irrigation is not an uncommon practice worldwide (Mohammad and Mazahreh 2003). As per the study of Gunnerson et al. (1985), in developing countries over 80% of the urban wastewater was used for agricultural purposes during 1985. In arid and semiarid western USA, reclaimed wastewater is regularly used to water golf courses and urban landscapes (Qian and Mecham 2005). Use of wastewater in irrigation has threefold impact viz. (1) source of irrigation water, (2) increase of the extent of irrigated areas and (3) source of nutrients.

Use of wastewater in crop production also widens the possibility of soil contamination, surface water pollution and environmental degradation (Ferrar et al. 2013). There is chance of building up of heavy metal pools in soils when irrigated with wastewater (Sharma et al. 2007). Further, uptake of heavy metals by crops may affect food quality and human health (Khan et al. 2008). Following these aspects of wastewater, this chapter describes the potential and limitations of wastewater in sustainable agriculture.

10.2 Types of Wastewater

Depending up on sources, wastewater may be of different types viz. wastewater from house-holds, agricultural wastewater, industrial wastewater, etc. (Vymazal 2009). Wastewater from rural and urban house-holds mainly carries domestic wastes and it may be black, brown and/or grey water. Black and brown water are generated from toilet (Tilley et al. 2014). Black water carries urine, human faeces while brown water does not contain urine (Tilley et al. 2014). These types of wastewater contain pathogens and thus should not be used in crop irrigation without any treatment (Hanaeus et al. 1997). Grey water is generated from bathroom, by cloth and dish-washing but not from toilet and thus may be used in irrigations in kitchen gardens (Maimon et al. 2010).

Different agricultural activities also produce a significant amount of wastewater (Vymazal 2009). Water carried out from agricultural lands is a rich source of fertilizer and pesticide residue (Wauchop 1978; Sims et al. 1998). Research indicates presence of pharmaceuticals, hormones and beauty product ingredients in the wastewater from cultivated fields (Pedersen et al. 2005). Apart from agriculture, other allied activities like piggery, diary, fish farm, etc., also produce wastewater (Vymazal 2009). Industrial sector is another major source of wastewater containing high concentrations of pollutants. The quality of wastewater may vary with type of industry like tannery industries, pulp and paper industry, textile industry, petrochemical and chemical industry, winery and distillery, food processing industry, etc. (Vymazal 2009). Presence of heavy metals in industrial wastewater is a major concern which may contaminate the environment (Nomanbhay and Palanisamy 2005). For this reason treatment of industrial wastewater is necessary before releasing/dumping or using for crop irrigation (Nomanbhay and Palanisamy 2005).

10.3 The Scenario of Wastewater Use in Irrigation

Land application of sewage and sludge is a widespread practice worldwide (Hussain et al. 2002). Globally at least 3.5 million ha area is irrigated either with untreated, partially treated, treated or diluted wastewater (Jiménez 2006). A big number of urban and sub-urban farmers often have no other choice than using wastewater for irrigation (Qadir et al. 2007). And it is more common in low-income countries (Bradford et al. 2003). Worldwide approximately 200 million farmers use below standard water for crop cultivation following the insufficiency of good quality water (Qadir et al. 2010). According to the World Health Organization (WHO 2006), wastewater irrigated crops feed 10% of global population.

Before the introduction of wastewater treatment technologies, disposal of wastewater in agricultural fields was a strategy in many cities of Europe and North-America to prevent water body pollution (Sustainable Agriculture Initiative Platform 2010). In modern time, wastewater is used as source of plant nutrients in many developing countries like India, Jordan, Palestine, South Africa, Nepal, Malaysia, Sri Lanka, Costa Rica (Sustainable Agriculture Initiative Platform 2010). In Pakistan, about 26% of the total vegetable production is irrigated with urban wastewater (Drechsel 2009) while cropland under wastewater irrigation is responsible for 80% vegetables production in Vietnam (Ensink et al. 2004). In the beginning of twenty-first century, China accounted for the highest area being irrigated with untreated wastewater in the world (Xianjun et al. 2003). On the other hand, Chile, Mexico and Israel are the countries with more use of treated wastewater for irrigation (Drechsel 2009). Country wise estimated area of productive use of wastewater in agriculture is presented in Fig. 10.1.

10.4 Use of Wastewater in Irrigation as an Alternative Source of Nutrients

Wastewater contains nutrients and thus its use for crop irrigation may lead to higher productivity (Parsons et al. 2001; Jiménez 2006). It can be used as a supplementary source of plant nutrients (Rusan et al. 2007). In comparison to freshwater, maximum crops give higher yield when irrigated with wastewater (Hussain et al. 2002).

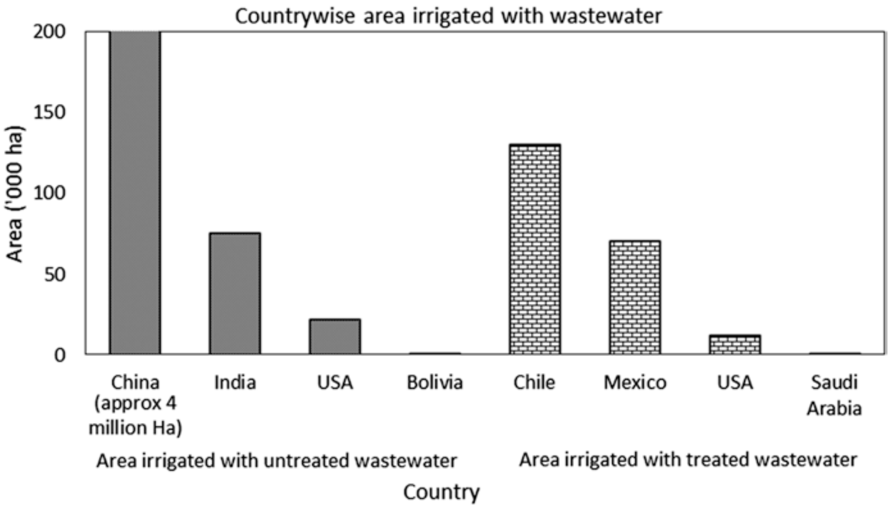

Fig. 10.1 Country wise area irrigated with wastewater (Source: Sustainable Agriculture Initiative Platform 2010)

Specifically, leafy vegetables like cauliflower, cabbage, spinach grows better under wastewater irrigation (Murtaza et al. 2003). The impact of wastewater application of soil fertility and quality depends on source and quality of wastewater, type of soil and nature of crops grown (Hussain et al. 2001). A study by Mohammad and Mazahreh (2003) indicates increase in soil organic matter through treated wastewater application. However, this study suggests the requirement of efficient treatment for reduction in salt content in wastewater. In a field experiment, application of olive oil mill wastewater lead to change in surface soil chemical properties like soil organic matter, nitrogen and phosphorus (Cabrera et al. 1996). As per Kaur et al. (2012), irrigation with wastewater may save 25–50% nitrogen and phosphorus use in fields and can increase crop productivity. Moreover, use of wastewater in crop irrigation results possible increase of land area under cultivation as well as cropping intensity (Scott et al. 2001).

Treatment of wastewater is important before application to agricultural fields (Pedrero et al. 2010). However, Kiziloglu et al. (2008) have found better yield and nutrient uptake by cauliflower and red cabbage when irrigated with untreated in comparison to treated wastewater. As per their suggestion, even untreated wastewater can be used for crop cultivation for short time span. In another study, Melia et al. (2002) have found increase in soil available nutrients and better metabolic efficiency of micro-organisms, specifically in dry season, when irrigated with lagooned wastewater. Irrigation with secondary treated wastewater resulted increased forage crop production in Jordan (Mohammad and Ayadi 2004). A study conducted in Zimbabwe also depicted significant accumulation of organic matter and other essential nutrients in soils amended with sewage sludge for 19 years (Nyamangara and Mzezewa 2001). Positive impact of recycled municipal effluents on soil nutrient status and crop yield has also been reported by Feigin et al. (1984) and Bielorai et al. (1984).

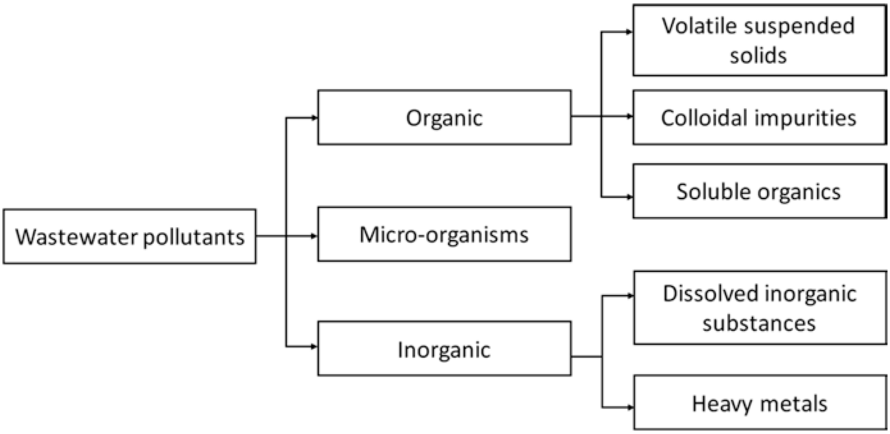

Fig. 10.2 Types of pollutants present in wastewater

10.5 Wastewater as a Source of Soil Pollutants

In many areas, undiluted or untreated wastewater is deliberately used as it delivers nutrients and is economical (Keraita and Drechsel 2004; Scott et al. 2004). However, using wastewater in this manner can pose a serious problem to soil and the whole ecosystem (Hussain et al. 2002) as it may carry appreciable amounts of heavy metals like arsenic, cadmium, chromium, mercury, lead, zinc, etc. (Mojiri and Amirossadat 2011). Long term application of industrial wastewater on agricultural lands might contribute to build-up of elevated concentration of toxic metals in soil and plants (Rattan et al. 2005; Singh et al. 2012). Further, microbial contamination is common in urban wastewater and can cause several diseases through waterborne or food borne route (Toze 2006).

Use of domestic sewage in agriculture also leads to soil and environmental pollution (Zhang et al. 2008). Wastewater from rural areas is generally characterized by organic and inorganic contaminants which are originated from dissolved contents of fertilizers, chemical runoff (such as pesticides), livestock manure and human activities like bathing, cooking, cleaning (Hussain et al. 2002). The type and characterization of common pollutants present in wastewater has been illustrated in Fig. 10.2 and Table 10.1, respectively.

10.6 Impact on Crop and Human Health

Irrigation with wastewater provides an important source of valuable plant nutrients and thus increase in yield is common effect (Jiménez 2006). Besides valuable plant nutrients, wastewater may carry different toxic minerals and biological agents which may results in less productivity and decline in crop quality parameters (Zavadil 2009). Wastewater irrigation over the years results heavy metals

Table 10.1 General characterization of pollutants present in wastewater

Type of pollutant	Sub-type	Components
Suspended solids	Volatiles suspended solids	Benzene, toluene, xylenes, dichloromethane, trichloroethane and trichloroethylene
	Colloidal impurities	Clay and silica, $Al(OH)_3$, $Fe(OH)_3$, organic waste products, colouring matter
Pathogens	Bacteria	*Escherichia coli*, *Salmonella* sp., *Shigella* spp., *Vibrio cholera*, *Bacillus anthracis*, *Clostridium tetani*, *Clostridium botulinum*
	Viruses	Enteroviruses, Hepatitis A, Poliovirus, Rotavirus
	Protozoans	*Entamoeba histolytica*, *Giardia lamblia*, *Cryptosporidium*
	Fungi	*Actinomycetes* sp., *Aspergillus* sp., *Candida albicans*
	Worms	*Ascaris lumbricoides*, *Schistosoma mansoni*, *Taenia saginata*, *Trichuris trichiura*, *Enterobius vermicularis*, *Ancylostoma duodenale*
Organic micro-pollutants	Pesticides, cosmetics, detergents	Hydrocarbons, solvents, surfactants, pentachlorophenol, DDT, sulphonated oils, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, organic-produced endotoxins, glucans
Inorganic substances	Dissolved inorganic substances	Sodium, calcium, nitrate, ammonia, sulphide, chloride
	Heavy metals and metalloids	Arsenic, cadmium, lead, nickel, mercury,
	Radioactive elements	Radon, uranium
Pharmaceuticals	Unused medications	From domestic, hospitals

Source: Partly adopted from Cheremisinoff (2002) and Hussain et al. (2002)

accumulation in soils (Rattan et al. 2005). The major consequence is inhibition of plant growth processes and curbed photosynthesis resulting in lower biomass and yield (Lin et al. 2005). Moreover, pathogen present in wastewater causes soil-borne diseases in plants (Bonanomi et al. 2006). Wastewater parameters and few plant physiological and biochemical responses are shown in Table 10.2.

Irrigation with wastewater also affects human health in both positive and negative ways. Wastewater use helps to cultivate food grains in water limiting situations and increases the quality of life by reducing malnutrition among poor (Jiménez 2006). However, negative effects of wastewater irrigation, due to its pathogenic loads, are very unfortunate. Infestation by bio-agents is a risk primarily to field workers and their families and secondarily to the consumers of the wastewater irrigated food products (Zhang et al. 2008; Chandran et al. 2012). Health hazards from the eggs of parasitic worms is a concern under wastewater use (WHO 1989). Further, diseases like cholera, typhoid, giardiasis are also very common with use of wastewater (Blumenthal et al. 1996).

Table 10.2 Plant responses to wastewater irrigation

Wastewater parameters	Plant responses
Essential plant nutrients: nitrogen, phosphorus, potassium, etc.	Enhances crop production Excess nitrogen causes nitrogen injury, excessive vegetative growth, delayed maturity Excessive nitrogen and phosphorus consequences eutrophication
Dissolved inorganic ions: sodium, calcium, magnesium, chlorine	Results soil salinity, sodicity and physiological draught in plants Phytotoxicity, leaf-tip burn
Heavy metals	Reduced growth, less presence of chlorophyll and carotenoids is observed in *Brassica juncea* under cadmium and lead toxicity. Cadmium toxicity also affects guard cell regulation Toxocity of iron, copper and cadmium consequences decline in chlorophyll and enzymatic (like catalase, ascorbate peroxidase, glutathione reductase) activities Lead toxicity results stunted growth of plants, chlorosis. It obstructs photosynthesis, disturbs mineral nutrition, water balance, plant hormonal balance Arsenic toxicity results decline in plant chlorophyll and carotenoid content. Further, higher arsenic concentration results sterility, unfilled florets and curbed growth Zinc toxicity in plants results subdued metabolic functions, retarded growth, chlorosis, senescence Excess of copper is cytotoxic. It affects germination, seedling length, causes retarded plant growth, chlorosis Mercury toxicity in plants results physiological disorders. Further, it hampers mitochondrial activity and other cellular metabolism Seed germination, photosynthesis, electron transport system and normal enzyme activities in plant body are affected severely due to chromium toxicity
Pathogens: Bacteria, virus	Causes plant diseases

Source: Asano et al. (1985), Gallego et al. (1996), Mascher et al. (2002), Perfus-Barbeoch et al. (2002), Duxbury et al. (2003), Sharma and Dubey (2005), John et al. (2009) and Nagajyoti et al. (2010)

Presence of heavy metals in wastewater and their bio-magnification also can cause chronic and severe health problems (Mojiri and Amirossadat 2011). Continuous consumption of foods, grown with arsenic contaminated wastewater, leads to its accumulation in human skin, hairs and nails and increases the risk of skin cancer, lung cancer and heart disease (Kapaj et al. 2006). Presence of cadmium in irrigation wastewater is also very hazardous as human body easily preserves and accumulates cadmium and it severely affects kidney, causes bone impairment and even lung cancer (Bernard 2008). A study by Cui et al. (2005) has found problem of renal dysfunction in people affected by soil contamination of cadmium and lead. Lead toxicity is also associated to anaemia, different neurological problems, hypertension (Goyer 1990). The notorious Minamata incident of Japan, which resulted a death toll of thousands, was caused by mercury toxicity from unregulated dumping of industrial wastewater (Harada 1995). Mercury consumption also may cause various neurological, cardiac, reproductive, genetic disorders in human (Zahir et al. 2005). Likewise, exposure to chromium through wastewater irrigated food chain may cause damage to human DNA and chromosome (Dayan and Paine 2001).

10.7 Conclusion

In modern world, where there is tremendous pressure on freshwater reserves, wastewater use in crop irrigation is unavoidable. Further, area under wastewater irrigation may increase in near future, specifically in the urban and sub-urban areas. In this situation, the best possible way out is rigorous monitoring and management. While, grey water from house-hold can be allowed to be used directly, strict surveillance should be on the regular treatment of industrial wastes and municipal sewage and sludge before dumping in soil. Further, there is requirement of continuous awareness campaign for the marginal of the small scale farmers regarding the positive and negative side of wastewater application in agriculture. The goal of the future will be optimization of the beneficial utilization of wastewater in agriculture, minimizing its detrimental impacts.

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Eco-friendly Nitrogen Fertilizers for Sustainable Agriculture

11

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Abstract

Agriculture meets two great sustainability challenges: first one is ability to provide nutrition to the world population and another one is to improve ecosystem services to maintain clean air, water, and other benefits to humanity. Appropriate nitrogen management is one of the primary challenges in agricultural production. Its application to agricultural and horticultural crops in conventional chemical forms causes significant increase in crop yield. Generally, farmers apply overdoses of chemical fertilizers in their agriculture field in order to maximize the crop productivity and about 50–70% of the applied conventional chemical fertilizers get lost in the environment due to leaching, runoff, emissions and volatilization in soil, water, and air. It causes agronomical, economic, environmental concerns, and health threats. Organic manures (OM) and bio-fertilizers are considered as possible alternatives for eco-friendly, economic, and organic agriculture, however, due to problems of limited availability and bulk transport of manures and low efficacy of OM and microbial bio-fertilizers, the use of conventional chemical fertilizers is still in practice in main stream agriculture. Slow (controlled) release fertilizers (SRFs) that release the nutrients slowly or synchronized with the growth rate and physiological need of plants increase the nutrient recovery to a great extent and minimize the nutrient losses and the resultant environmental hazards caused by the excessive use of soluble chemical fertilizers.

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The SRFs are new type of eco-friendly plant nutrient providers that can be used as a feasible alternative to the chemical fertilizers. However, the cost effectiveness of the commercial SRF formulations and lack of awareness on ill effects of chemical fertilizers are major limitations for replacing the conventional chemical fertilizers by slow release fertilizers and other customized fertilizers especially in the developing world. We have developed organic matrix based slow release fertilizers using biodegradable non-toxic and locally available agro-waste/agro-products which are low cost, highly efficient, and eco-friendly that enhance crop productivity as well as soil fertility in the applied fields. It is evident from the earlier reports and our own work that during consistent supply of exogenous N either through the split doses or through the SRFs, accumulation of inorganic N occurs in aerial sinks of plants, i.e., mature leaves and grains increases. A manipulation of source–sink relationship, transport and remobilization of the nutrients, and enhanced assimilation of accumulated inorganic N in plants during reproductive phases, in addition to application of the customized fertilizers, will lead to alleviate yield and improved food quality. Present chapter critically review the potentiality of N based SRFs and genetic manipulations for enhanced NUE for sustainable plant productivity as a viable alternative to the green revolution based nutritional packages.

Keywords
Bio-fertilizers • Chemical fertilizers • Customized fertilizers • Nitrogen use efficiency • Organic manures • Slow release fertilizers

11.1 Introduction

Application of fertilizers for providing nutrition to the plants has been a common practice in agriculture for improving crop growth and yield (Fageria 2016). Plants are responsive to the applied nitrogen that comprises most of the essential macromolecules and metabolites that relate to their vegetative and reproductive growth and metabolism. Nitrogen enhances crop productivity and biomass production, as agricultural soil is deficient in N worldwide. In particularly developing countries, application of inorganic fertilizers is considered needed to meet the requirement of the increasing population (Abrol et al. 1999; Chanda and Sati 2005; Monem et al. 2010; Wang et al. 2010). To feed the burgeoning population, the global food production is to be double. For improving food production, additional nitrogen requires in nitrogen deficient soils.

Nitrogen application rates have increased about 15 times during the last five decades, whereas its accumulation in the grain has increased about 4 times only (Singh 1995a, b; Singh et al. 1998, 2006, 2008, 2010). Maximum of the applied nitrogen is lost in soil, water, and air and remaining 30–50% taken by plants that get converted into organic nitrogenous molecules, e.g., amino acids, proteins, amines, amides, and aromatic compound. It has been observed that even from the N taken in plants, a significant amount is left unassimilated in the foliage and other tissues of the plants especially during stresses or when chemical N is supplied consistently (Dahiya et al. 2004; Kumar et al. 2013a, b). Of the total amount of the N applied to the plants, almost 50–70% get lost through leaching, erosion, surface runoff, and volatilization while only 30–50% in actual is taken up by the plants. The N losses through different routes mentioned above not only deteriorates the quality of water and the ecosystem but also contributes in elevating the concentration of greenhouse gases, thus the global warming (Adesemoye et al. 2009; Rawat et al. 2010; Weligama et al. 2010; Jiang et al. 2010).

This problem needs an urgent attention which can be addressed through the various practices, technologies, and improvement programs that could contribute to increase in nitrogen use efficiency (NUE) (Giagnoni et al. 2016). Such practices and programs contribute in improved timing of fertilizers application, i.e., fertilizers application at periods of greatest crop demand, application of fertilizers near the plant roots, split doses of small quantity of fertilizers, planting crops and crop cultivars that have higher NUE, use of cover crops, reduced tillage; closing of nitrogen cycle such as applying livestock and human waste in appropriate amount, use of slow and controlled release of nutrients, organic manures, green manures, microbial bio-fertilizers, use of crop rotation or inter cropping, and agro-forestry and landscape-scale management (Sary et al. 2009; Singh et al. 2011; Granta et al. 2012; Azimi et al. 2013).

The Integrated Plant Nutrient System (IPNS) adapts plant nutrition to a specific farming and particular yield, the physical resource base, the available plant nutrient sources, and the socio-economic background (Singh et al. 1998, 2006, 2008, 2010; Prasad 1999) are also the major components of ecological and sustainable farming system (Agami 2016; Hernandez et al. 2016).

Use of organic manures and use of bio-fertilizers are often considered as alternatives to the chemical fertilizers (Gopinath et al. 2008). However, the limited availability of organic manures to meet the bulk requirement of the agricultural fields worldwide and its lower efficacy are major bottleneck to maintain the crop productivity up to a desired level. The idea of using co-compost of cattle manure and chemical fertilizers to improve the efficacy of FYM has been attempted (Matsushita et al. 2000; Gopinath et al. 2008), however, the feasibility of this technique in large scale plant agriculture is in question. Various genera, species, strains, and ecotypes of microbial inoculants have been identified as N_2-fixers and plant growth promoters. A significant number of plant growths promoting rhizobacteria (PGPRs) have been commercially made available to public and private agencies (Wu et al. 2005; Gopinath et al. 2008). However, these bio-fertilizers have not been adopted by the farmers at large scale to replace the requirements of harmful conventional chemical fertilizers primarily due to their low efficacy, less awareness to the environmental and health related problems using chemical fertilizers, and poor technical support to farmers about sustainable handling and affectivity of microbial bio-fertilizers, as they are living organisms and may suffer from the stresses during storage, transport, and availability (Singh et al. 2006, 2008, 2010; Gopinath et al. 2008).

The use of slow/controlled release fertilizers often synchronized with the physiological need of plants is considered as one of the most viable alternatives for the sustainable plants productivity (Singh et al. 1998; Saigusa 1999; Padmaja et al. 2000; Diez et al. 2000; Dahiya et al. 2004; Granta et al. 2012; Yushi et al. 2011). Slow/controlled release and others customized fertilizers are new generation plant nutrients, which can be efficient and eco-friendly though most of the commercially available formulations are expensive and farmers in controlled agricultural economy or poor economy are unable to afford its use for most of the crops (Singh et al. 2006, 2008, 2010; Kumar et al. 2012, 2013a, b, 2014).

Several formulations of slow release fertilizers (SRFs) have been developed by different processes which include (a) condensation of small nutrient molecules, (b) coating to a matrix, (c) super granules adsorbed or immobilized nutrients into a matrix, and (d) amending nitrification and urease inhibitors (Yamamoto et al. 2016). The slow release fertilizers that are adjusted with nitrification inhibitors are also known as stabilized fertilizers. Customized fertilizers are the term that has been introduced recently for the modified form of conventional chemical fertilizers which reduces the nutrient losses and enhance its efficacy (Granta et al. 2012; Yushi et al. 2011).

The application of SRFs has been commercialized only in few countries like Japan, USA, Israel, Australia, China, and Europe and that too for limited crops. Despite of the fact that the developing countries like India have much pressure on them for meeting the demand of their escalating population, they have not adopted SRFs in its main stream agriculture yet. The major limitations to realize the potentials of SRFs/CRFs in the contemporary crop agriculture systems include (a) high cost involved in the production of SRFs/CRFs, (b) comparatively higher prices of SRFs over the conventional soluble chemical fertilizers (subsidized), bio-fertilizers, and organic fertilizers (c) lack of appropriate endogenous technology, (d) lack of appropriate appreciation and awareness on SRFs by the existing agricultural network. We have developed low cost organic matrix based super granules which contain biodegradable, cost effective, non-toxic and locally available agro-waste, organic binders, and chemical fertilizers in very low quantity or microbial biofertilizers in higher quantity and found that it is more effective than the conventional chemical fertilizers. We have investigated our newly developed SRFs for their efficacy for wheat, rice, Indian mustard, sesame, menthe, garlic, chillie, and *Rauwolfia serpentina* and have observed that these formulations are highly effective for all the crops over the conventional chemical fertilizers. The cost affectivity has also been estimated and these SRFs have been found to be cost effective. It also increases the soil fertility in terms of nutrient and microbial enrichment (Dahiya et al. 2004; Singh et al. 2006, 2008, 2010; Sharma et al. 2011, 2012; Kumar et al. 2012, 2013a, b, 2014).

This chapter critically reviews the process of nitrogen assimilation in plants, practices, and problems related with heavy loading of conventional chemical fertilizers potentials and limitations of alternative plant nutrient, e.g., organic manures, bio-fertilizers, and slow release fertilizers to understand the need and evaluation of new generation, eco-friendly plant nutrients for the sustainable plant agriculture in the era of climate change, and global warming.

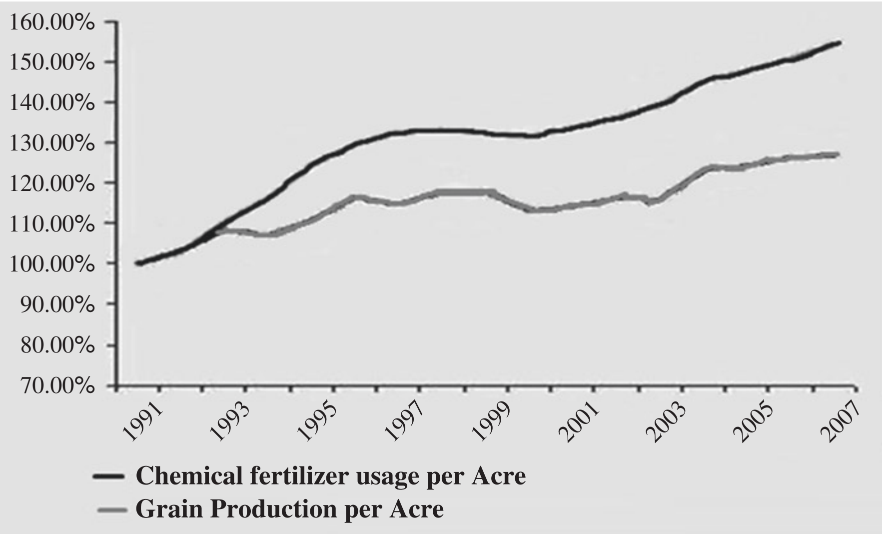

Fig. 11.1 Relation between fertilizers use and plant productivity (http://www.getfilings.com/sec-filings/091217/Yongye-International-Inc_8-K/v169258_ex99-2.htm#b)

11.2 Application of Soluble Chemical Fertilizers and Crop Productivity

Exogenous application of chemical N in the form of fertilizers like urea, ammonium nitrate, diammonium phosphate, etc., for enhanced crop productivity has been a common practice especially after adoption of the green revolutions package. It has been found to be directly proportional to the yield of major cereals, e.g., rice, maize, and wheat (Fig. 11.1). In many countries, economic subsidy on chemical fertilizers is provided to the manufacturers for controlling the price of agricultural products. (Shiferaw et al. 2016). In addition to the economic input very high quantum of energy is consumed by the fertilizers industry to produce these chemical fertilizers. Till the ill effects of these conventional chemical fertilizers and its potential alternatives were not known, it was considered as essential requirements of crop production (Fig. 11.1).

11.3 Nitrogen Assimilation in Plants

Most plants obtain nitrogen from soil in the form of NO_3^-, and NH_4^+ largely derived from the fertilizers, microbial degradation of the nitrogenous wastes, or through biological nitrogen fixation (Figs. 11.2 and 11.3). The inorganic forms of N, i.e., nitrate, nitrite, and ammonium, are assimilated by the plants including bacteria into the primary amino acid, L-glutamic acid (Singh 1995a, b; Srivastava 1995; Singh and Jaiwal 1999). Ammonium is the entry port for incorporation of inorganic N into

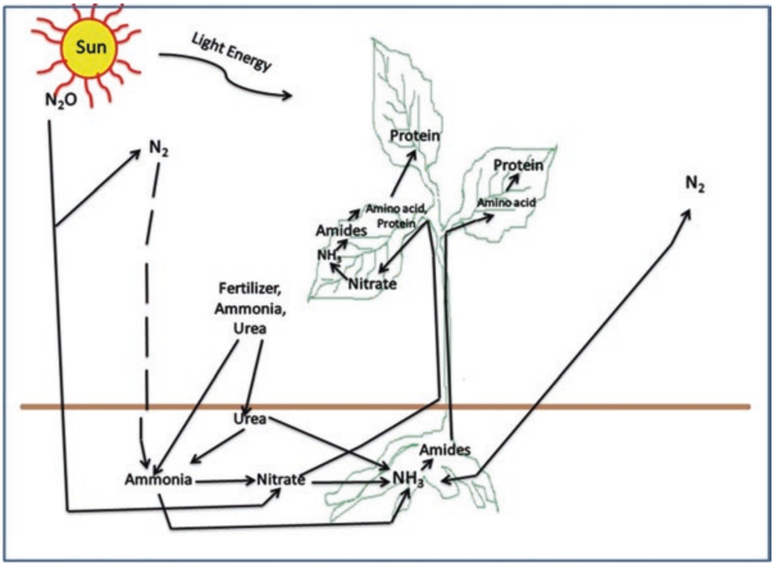

Fig. 11.2 Nitrogen in relation to soil, plants, and atmosphere (adopted from Hardy et al. 1975)

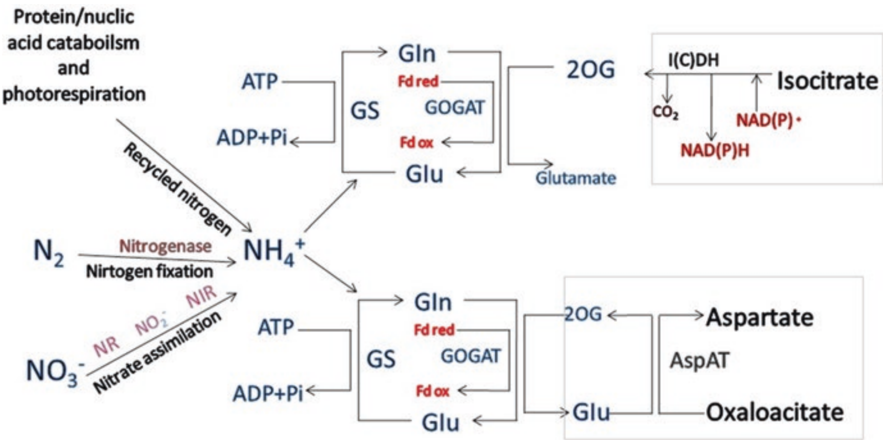

Fig. 11.3 A simplified scheme showing ammonium assimilation with glutamine synthetase–glutamate synthase (GS–GOGAT) pathway and production of 2-oxoglutarate (2OG) either by an isocitrate dehydrogenase [I(C)DH] or by an aspartate aminotransferase (AspAT) (adopted in Trends in Plant Science)

the organic cycle (Figs. 11.3 and 11.4). The primary source of nutrient nitrogen in most of the arable soils is nitrate while ammonium serves as the chief source of nitrogen where anaerobic condition prevails. The nitrogen (N_2) present in the atmosphere gets transformed biologically into ammonium either through symbiotic fixation or non-symbiotic fixation. The reduction of nitrate to nitrite is mediated by the

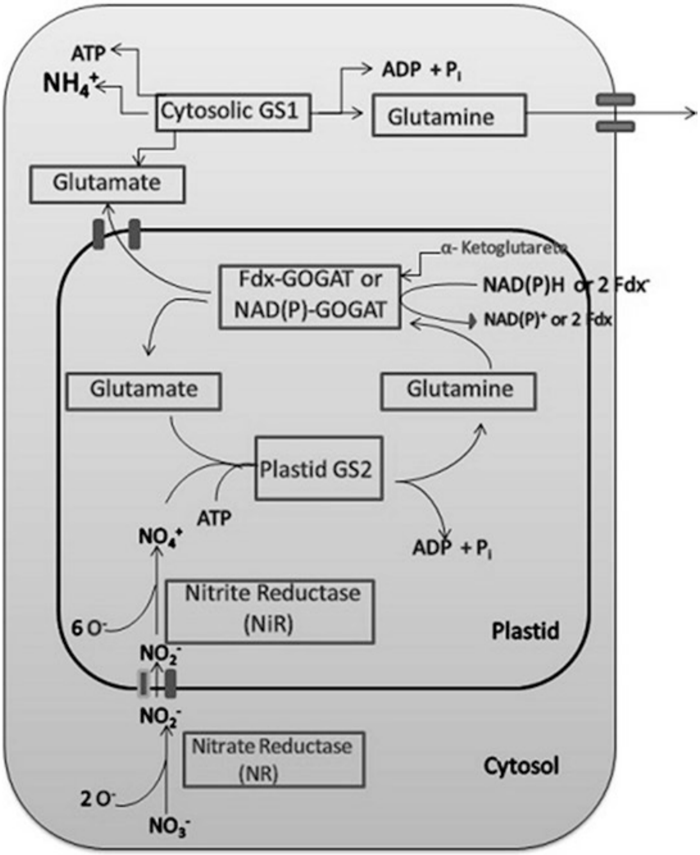

Fig. 11.4 Partitioning of inorganic nitrogen assimilation in different intracellular organelles in plants (http://www.uky.edu/~dhild/biochem/24/lect24.html)

enzyme-nitrate reductase (NR). The reduced nitrite gets further reduced to ammonium in presence of the enzyme nitrite reductase (NiR). In the next step, ammonium gets assimilated into L-glutamine in the presence of L-glutamine synthetase (GS) followed by subsequent production of L-glutamic acid. This step involves through incorporation of amide nitrogen of the glutamine into 2-oxoglutarate which is catalyzed by L-glutamate synthase (Fd-GOGAT and NAD(P)H-GOGAT). In this pathway, one L-glutamic acid molecule produces one molecule of L-glutamine and two molecules of L-glutamate with a net benefit of one L-glutamate (Singh and Srivatava 1982, 1986). In early 1970s, this pathway was discovered in bacteria and then in plants. Another enzyme, for which at least 14 isoforms have been reported, is L-glutamate dehydrogenase (NADH-GDH and NAD-GDH). This enzyme catalyzes direct amination and deamination reaction of ammonium to and from L-glutamic acid and is found in almost all the living organisms. Being a reversible catalytic system, GDH pathway of ammonium assimilation is considered as an alternative pathway which generally operates under the stresses when ammonium is available in excess amount. The assimilated N gets incorporated into proteins, nucleic acid, and many other metabolites which are essential for the functioning of living organisms.

11.4 Nitrogen Losses in Environment

It has been noticed that the most of the hybrid varieties of cereals and other crops introduced as a package of green revolution in early 1960s are highly responsive to applied chemical nitrogen fertilizers like urea or diammonium phosphate, etc., and heavy irrigation. To enhance crop productivity excessive loading of these fertilizers has been a common practice in the contemporary plant agriculture globally (Monem et al. 2010; Wang et al. 2010). The excessive use of N fertilizers increases root biomass and as a result high absorption of the various nutrients from the soil occur, which cause deficiency of other nutrients including micronutrients (Li et al. 2015; Zhu et al. 2012; Zhang et al. 2013). As only 30–50% of the applied soluble nitrogen gets absorbed by the plants and remaining gets lost due to leaching, runoff, volatilization, and emissions (Singh et al. 2006, 2008, 2010), the losses account for contaminating ground and surface water bodies, which cause eutrophication and hypoxia in water and many other environmental degradations and health hazards (Adesemoye et al. 2009; Weligama et al. 2010; Abhilasha et al. 2011, 2012). The exposure to high levels of nitrate and nitrite induces many kinds of toxicity in zooplanktons and aquatic animals which creates health hazards in cattles, ruminants, and human beings (Table 11.1). The nitrite in combination with organic pollutants and other nitrogenous xenobiotic compounds are reported to affect the nervous system, induce heart diseases, and cause many types of cancers.

Nitrate is a highly soluble anion and, unlike NH^{4+}, is not readily adsorbed or fixed by the soil. Plants can take up NO_3^- rapidly only during the fast growing phase, and thus agricultural soils are often prone to “leak” substantial quantities of

Table 11.1 Contamination of surface and ground water by nitrate and nitrite

Place	Level of NO_3^- (mg L^{-1})		Level of NO_2^- (mg L^{-1})		References
	Ground water	Surface water	Ground water	Surface water	
Lucknow, India	38–114	34.96–51.58	0.07–0.29	0.12–0.26	Rawat et al. (2010, 2012)
Karnataka, India	143.66	–	–	–	Jeevanandam et al. (2007)
Makurdi, Nigeria	45–148	–	–	–	Maxwell et al. (2010)
Rawalpindi, Pakistan	45–1125	–	–	–	Kazmi and Khan (2005)
Asir, Saudi Arabia	–	–	–	0.07–0.089	Khanfar (2010)
Permissible limit	45	10	3.29	0.06	

Table 11.2 Leaching and losses of nitrogen from the agricultural fields on application of conventional chemical fertilizers

Cereals	Fertilizers used	Leaching and loses of nutrients	References
Rice	P_2O_5 (75 kg ha^{-1}), K_2O (75 kg ha^{-1}), urea (95–325 kg N ha^{-1})	NO_3^- leaching	Zhang et al. (2013)
Wheat	P_2O_5–90 kg hm^{-2}, urea–225 kg hm^{-2}	Losses of N, P content in soil and water	Bao-guo et al. (2012)
Wheat	130 kg N/ha, 90 kg P_2O_5/ha, 36 kg K_2O/ha	NO_3^- leaching and N_2O emission	Zhu et al. (2012)
Rice	P_2O_5 = 56.25 kg ha^{-1}, calcium magnesium phosphate = 468.8 kg ha^{-1}, potassium chloride = 90.8 kg ha^{-1}	NH_3 volatilization	Xu et al. (2012)
Wheat	N-fixation-N besides dry atmospheric deposition (6–7 kg/ha/year), liquid organic fertilizers (84 kg N/ha)	NO_3^- leaching and N_2O emission	Nylinder et al. (2011)
Wheat	Urea	NO_3^- leaching (0–60 cm)	Marcelino et al. (2011)
Maize	P_2O_5 = 92 kg ha^{-1} K_2O = 81 kg ha^{-1}, Urea = 0–189 kg ha^{-1}	NO_3–N leaching	Gheysari et al. (2009)

NO_3^- in drainage water towards surface runoff or ground water. Nitrate leaching losses are generally greater from poorly structured sandy soils than well-structured clay soils (Zhu et al. 2012, 2013).

In addition to nitrate leaching, nitrous oxide and nitric oxide emissions primarily by the microbial nitrification and de-nitrification and ammonia volatilization are two other important processes that cause N-loss from soil and plants to the atmosphere (Table 11.2) (Merrington et al. 2002; Akiyama et al. 2000; Jiang et al. 2010). Conditions favoring de-nitrification are the presence of adequate NO_3^- levels, denitrifying organisms, high soil water contents, and potential anaerobic conditions. In addition, the most important rate determining factors are soil temperature and the amount of readily available carbon substrate in soil. The de-nitrification can be very significant N loss process in agricultural soils, particularly from heavy soils in wet conditions. This process not only causes an economic loss to the farmers by reducing the availability of mineral N for crop uptake (by emissions of NO and N_2O are pollutants that may pose an environmental hazard) but also damages the natural and semi-natural ecosystems and causes global warming through enhancement of NO*x* in atmosphere (Zhu et al. 2012).

Though retention of NH^{4+} in the soil on negatively charged cations causes lesser risks of its leaching, gaseous losses of NH_3 do occur in agricultural systems including emission from the soil. In Europe, the largest source of atmospheric pollution by NH_3 is agriculture, although oceans and biomass burning are also important and an estimated 60% of global emissions are from anthropogenic sources (Xu et al. 2012). The agricultural systems involving livestock (especially intensive production system) are the most significant sources of gaseous losses of NH_3. Most of the developing countries possess such agricultural systems and thus are prone to NH_3 volatilization. In arable soils, the greatest loss occur when ammonical fertilizers or urea are applied under alkaline conditions (Xu et al. 2012). Ammonia loss resulting from surface volatilization is aggravated by high soil temperature and drying conditions, but can largely be prevented by placing fertilizers below the soil surface or working them thoroughly with the top soil (Tisdale et al. 1993; Merrington et al. 2002; Xu et al. 2012). The excessive use of N fertilizer is known to cause enhanced volatilization of ammonia and emissions of NO*x* gases which are very potential threat to the global warming (Jiang et al. 2010). Organic manures also produce methane in anaerobic conditions (Jayadeva et al. 2009).

11.5 Organic Manures and Microbial Bio-Fertilizers

On one hand, the agricultural practices such as application of chemical fertilizers and pesticides, use of energy based tools and equipments, and consumption of high water content have raised production cost and have degraded the quality of soil, water, and ultimately the biosphere, on the other. Therefore, there is an urgent requirement to develop inventive procedures, tools, techniques, production, transportation, distribution, and marketing that are based on low input in agriculture, sustained productivity, and sustainable resource management.

In organic farming systems, organic manures like compost, vermicompost, cow-dung, and farm yard manure (FYM) have been recommended as an alternate to the chemical fertilizers (Ardakani et al. 2011; Vaneeckhaute et al. 2015). However, these manures are relatively slow in action and thus required to be applied in bulk quantity to maintain high crop yields, but in recent years due to rapid urbanization and industrialization, the populations of cattle and other ruminants have recorded rapid decrease, thus the availability of organic manures in bulk is difficult. The practices to convert organic wastes from agricultural and urban sources into manure at large scale have yet to be established (Sary et al. 2009; Singh et al. 2011, 2013).

Another economically attractive and ecologically sound alternative to the chemical fertilizers which increases the soil fertility and crop production in sustainable farming is bio-fertilizer (Wu et al. 2005; Kundu et al. 2009). Bio-fertilizers are the products containing living cells of various types of microbes that have the ability to convert the unavailable forms of nutritional elements to available forms through biological processes. In recent years, bio-fertilizers have been emerged as a vital component of the integrated nutrient management programs (INMP). Several strains of *Azotobacter*, *Rhizobium*, *Bradyrhizobium*, *Azospirillum*, *Pseudomonas*, *Bacillus*, and *Acetobacter* have been developed in recent years as bio-fertilizers for cereals, pulses, vegetables, oil seeds, cotton, sugarcane, and wheat (Mahajan et al. 2003; Ogut et al. 2005; Shaukat et al. 2006; Broschat and Moore 2007; Adesemoye et al. 2009) (Table 11.3). Although, bio-fertilizers could prove as a good alternative to chemical fertilizers but when compared with recommended doses of chemical

Table 11.3 Responsiveness of cereals to the application of different organic/bio-fertilizers

	Organic/bio-fertilizers	Response observed	References
Wheat	*Anabaena*, *Azotobacter*, *Pseudomonas*, *Serratia*, and *Mesorhizobium*	N-fixation performance, plant growth parameters	Swarnalakshmi et al. (2013)
Rice	FYM, Azolla microphylla, BGA	Plant growth, grain, and straw yield	Singh et al. (2013)
Barley	N-bio-fertilizers: (Nitroksin, Nitrokara, and Supernitroplass; P-bio-fertilizers: phosphate barvar2, biozarr, and superplass	Seed yield	Azimi et al. (2013)
Maize	*Pseudomonas* fluorescens, Enterobacter radicincitans	P uptake and yield	Krey et al. (2013)
Mustard	*Azotobacter chrococcum*, *Bacillus* sp.	Crop growth rate, leaf area index, and harvest index	Banerjee et al. (2012)
Wheat	Integrated nutrient management (organic fertilizers, Urea, SSP, KCL, Nimco)	Growth attributes and yields of wheat	Singh et al. (2011)
Wheat	Cerealine, microbein (includes *Azotobacter*, *Azospirillum*, and *Bacillus* spp.)	Wheat yield, nitrogen levels	Kandil et al. (2011)
Wheat	*Azospirillum brasilense*, *Streptomyces* sp., *Glomus intraradices*	Absorption efficiency of nutrient in plant/grain, nutrient content in plant	Ardakani et al. (2011)
Wheat	*Pseudomonas*, phosphorus fertilization, urea, potassium sulfate	Growth parameter (root elongation and weight), straw, and wheat yield, P, K, and N uptake	Zabihi et al. (2011)
Wheat	*Azospirillum*	Shoot length, root length, shoot and root dry wt., root to shoot ratio	Ilyas and Bano (2010)
Wheat	Organic fertilizers, chicken manure, cerealine, i.e., *Azospirillum* spp.	Wheat yield and yield components	Sary et al. (2009)

fertilizers, its efficacy is relatively low in relation to the crop yield (Sary et al. 2009; Swarnalakshmi et al. 2013).

The microbial diversity is massive and its evolution as well as adaptations to the changing environment is really significant for improved nutrient management programmes. Bio-prospecting of soil microbes from different agro-climatic conditions for the purpose of isolation, selection, and improvement of plant growth rhizobacteria (PGPR) is a thrust area. The research in this field could provide new and improved strains of bio-fertilizers that can enhance the nutrient availability (Adesemoye et al. 2009; Sharma et al. 2011, 2012). The genera, species, strains, and ecotypes for symbiotic and non-symbiotic N_2 fixers, phosphate solubilizing bacteria (PSB), potassium solubilizing bacteria, and Fe solubilizing bacteria have already been discovered. Genetic modifications in particular microbes can be done by using conventional method and gene technologies. The selected microbes that are potential PGPR are needed to be optimized for their specific dose responses in various crops and for different agro-climatic conditions. New carriers of such microbes are yet to be discovered and designed for maintaining better and productive micro-environment to these bio-fertilizers during storage, transport, and application in the fields (Banerjee et al. 2012; Krey et al. 2013).

11.6 Slow (Controlled) Release Fertilizers and Plant Productivity

Though organic manures, green manure practices, bio-fertilizers, and co-composting of FYM and chemical fertilizers have been attempted as alternatives to overloading of chemical fertilizers, but none of them has emerged as a viable alternative that can be adopted in main stream plant agriculture at large scale.

Slow (Controlled) fertilizers (SRFs) have a potential for managing high crop productivity eliminating the risks associated with the soluble chemical fertilizers (Kumar et al. 2012, 2013a, b; Coppens et al. 2016). Unlike the rapidly available soluble fertilizers, SRFs are slow acting due to the delayed release of nutrients which are often available in bound/immobilized form in or into a non-toxic, biodegradable, and usually inert matrix. A good SRF should release the nutrients in rhizosphere at the rates and amounts that match the need of the growing plant (Saigusa 1999; Singh et al. 2006, 2008, 2010). According to the Association of American Plant Food Control Officials (1995), slow release fertilizer is defined as fertilizer containing plant nutrients in a form that delays its availability for plant uptake and use after application, or which extends its availability to the plant significantly longer than a reference rapidly available nutrient fertilizer such as ammonium nitrate or urea, ammonium phosphate, or potassium chloride. The technical interventions which could reduce the nutrient losses and provide nutrients to the plants for a comparatively longer duration could facilitate retention of the nutrients for longer duration (slow release fertilizers; SRFs) or its release in rhizosphere as per the nutritional requirements of the crop (controlled release fertilizers; CRFs) (Emilsson et al. 2007; Wu et al. 2008; Granta et al. 2012). It plays an imperative role in improving the fertilizer use efficiency by plants, thus mitigating environmental pollution and can be seen as an essential nutritional component of the sustainable agriculture (Zhao et al. 2010).

The SRFs can be coated (e.g., sulfur coated urea, polymer coated fertilizers, neem coated urea, etc.), uncoated, supergranules, or stabilized fertilizers (nitrification inhibitors, urease inhibitor, etc.) (Saigusa 1999; Singh et al. 2006, 2008, 2010; Babadi et al. 2015). Several commercial SRFs are available in market, which have many benefits over the conventional soluble chemical fertilizers. Some of these potential benefits are efficient use of nutrient by the crop, reduced nutrient losses and the resultant environmental and health hazards, reduction of salt and ammonia toxicity of crops (Fan and Li 2010; Zhu et al. 2012), lasting N supply, reducing

Table 11.4 Responsiveness of cereals to the application of different types of the slow/controlled release fertilizers

	Slow/controlled release fertilizers			
Cultivar	Form	Amount	Response observed	References
Rice	Controlled release N fertilizers	BBF (24% N–12% P_2O_5–12% K_2O); PCU (42% N)	Grain yield, N uptake, and N use efficiency	Yushi et al. (2011)
Wheat	Controlled released urea and urea	CRU–0 to 225 kg N/ha	Dry matter yield, grain or seed yield, seed N concentration	Granta et al. (2012)
Wheat	Controlled release urea fertilizers	75–225 kg N/ha	N release, nitrogen use efficiency, yield of grain and straw	Yang et al. (2011)
Wheat	Slow release fertilizers: liquid nitamin (L30), liquid nitamin (G30), granular nitamin (N42), granular nitroform (NF)	–	N-release in the form of NH_4-N, NO_3-N, soil type, soil temperature	Fan and Li (2010)
Wheat, barley	Controlled release urea	50–60 kg N ha^{-1}	Soil microbial biomass	Lupwayi et al. (2010)
Wheat	Polymer coated urea	PCU–0 to 168 kg N/ha, urea–56 N/ha	Effect of PCU in emergence of all varieties	Ingle et al. (2010)
Wheat	Urea, coated urea, uncoated urea	Urea–250 kg N/ha, coated urea–75 kg N/ha, uncoated urea–125 kg N/ha	Increased N content in soil, good crop yield	Wang et al. (2007)
Rice	Controlled release urea	Nongke CRF: 23-7-20; A Luxecote CRF: 20-6-10	Change of soil N, plant biomass, yield	Shuan-hu et al. (2007)
Wheat	Neem coated urea, i.e., neem cake, nimco, nimagold	–	Urease activity, urea transformation in soils and wheat yield	Singh et al. (2006)
Wheat	Green manure *sesbania sesban*, nitrification inhibitor, encapsulated calcium carbide (ECC) used	Urea + sesbania–107 mg/kg, ECC = 10% of N applied	Availability of NH_4^+ and NO_3^- in soil plants have been studied	Patra et al. (2006)

application cost, reducing heavy N dressing caused soil acidification, and synchronized uptake and assimilation of nutrient (Table 11.4). Various factors that can affect the efficacy of SRFs during application and its success rate to the agricultural fields have been quite adequately presented in the literature (Yang et al. 2011; Granta et al. 2012; Yushi et al. 2011). However, certain problems and issues need to be discussed to argue for the global use of SRFs as a viable alternative to the soluble chemical fertilizers.

Noticeable success in use of SRFs to the farmers' field has been limited to certain countries, e.g., Japan, USA, Israel, Australia, and those in Europe and that too for the few cropping systems. The developing world with extensive agricultural practices and pressure towards producing more to feed the burgeoning population have not been sensitized but for a few reports on SRF applications (Prasad 1998, 1999; Dahiya et al. 2004; Singh et al. 2006, 2008, 2010). Lack of appropriate endogenous technology, appreciation and awareness on SRFs by the present agricultural network in these countries, ignorance towards associated environmental as well as health threats and also increased price of these fertilizers over the conventional soluble chemical fertilizers, bio-fertilizers, and organic fertilizers may be seen as the major bottlenecks to use the potentials of SRFs in the contemporary crop agriculture systems in many regions of the world.

Another problem in use of SRFs relates to a caution of increased NO_3^- and NH_4^+ contents in the edible parts of the plants applied with SRFs as observed in many cases with split doses of the soluble chemical fertilizers, which may be toxic to the consumers. Abrol (1990) has pointed out that improving the availability of soil NO_3^- at later growth stages in wheat by increasing the frequency of splitting the total quantity of fertilizer N applied resulted in more N in the whole plant and in the grains. The organic forms of increased plant N may be beneficial; however, the unassimilated NO_3^-, NH_4^+, and nitrogen oxides can be harmful. We have recently noticed that NO_3^-, NO_2^-, and NH_4^+ contents of the leaves and grains of rice and wheat were significantly higher in plants during the vegetative and reproductive stages applied with SRFs as compared to no N or bio-fertilizers/chemical fertilizer supplied plants (Dahiya et al. 2004; Kumar et al. 2012, 2013a, b, 2014).

Herein certain formulations of SRFs that are based on use of organic matrix containing local non-toxic, biodegradable, and comparatively low cost matrix to bind with the chemical nutrients that have been developed and tested. The results showed significant results for major cereals, e.g., rice, wheat, and Indian mustard. Further investigations are required for the validation of the obtained result at larger agricultural fields (Dahiya et al. 2004; Sharma and Singh 2011; Sharma et al. 2012; Kumar et al. 2012, 2013a, b).

Use of low cost binders and other modifications to make SRFs novel yet cheaper option is needed to meet the challenges in the developing world. Significant efforts have been made in this direction which includes development of organic matrix entrapped bio-fertilizers granules. The results showed significantly higher efficacy as compared to the conventional bio-fertilizers which are available in the market. Application of low cost slow/controlled release fertilizers could serve as a useful alternative planning for the reduction of extensive use of split doses of high N-responsive hybrid crops. These fertilizers can retain high productivity with one basal application, reduce the load of chemical fertilizers, and minimize nutrient (N) losses to the environment. The selection of crop varieties for higher NUE or production of new hybrids/GMOs using hybridization and gene technologies for improved NUE in plants is required to be attempted to assimilate the unassimilated N in leaves and grains/fruits so that the efficacy of the applied N can be increased further and simultaneously the food products can be saved from the contamination of reactive N species which is toxic to animal, cattle, and human consumers.

11.7 Conclusions and Future Prospects

The above analysis of the pertinent literature indicates that the use of conventional chemical fertilizers especially N fertilizers which are often loaded in excessive amount is not sustainable for the future plant agriculture. New generation eco-friendly and cost effective plant nutrients customized for different cropping system, agricultural ecosystems, and agro-climatic conditions are required to be developed. The concept of organic farming which insists on organic input and organic products only is also not tenable as most of the biochemical and metabolic reactions which support life systems are based on chemical reactions and energy based regulations. All the vital molecules and processes that are essential for survival of living organisms are dependent on integration of physical, chemical, and biological activities. An ecological agriculture can be a future option for sustainable food production in which integrated plant nutrients systems, cost effective slow release fertilizers, and technologically amended microbial bio-fertilizers will be used in place of the conventional chemical fertilizers.

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Scope of Natural Sources of Potassium in Sustainable Agriculture

12

B.B. Basak and Binoy Sarkar

Abstract

Modern intensive agriculture leads to significant decline in soil K status due to crop removal without compensating through K fertilizer. Most of the K ores suitable for commercial K fertilizer production are distributed in few countries in the northern hemisphere (Canada, Russia, Belarus and Germany). India is completely dependent on foreign countries since its whole consumption of K fertilizer is imported. So, self-sufficiency in commercial K fertilizer is a major issue in developing countries like India. In this context, alternative sources of K have a promising future in the developing countries where commercial K fertilizers are imported for crop production. There are some low-grade but indigenous resources of K-bearing minerals which can be exploited as an alternative of the expensive imported K fertilizers. Direct application of these indigenous K minerals as well as bio-activation through potassium solubilizing microorganisms could be a quite promising K source. In this chapter, we have discussed the scope of naturally occurring K minerals (low-grade K minerals, silicate minerals and greensand) and indigenous sources of K (crop residue, manures, wood ash and seaweed) as well as K biofertilizer as a potential substitute of commercial K fertilizer for sustainable agriculture in the developing countries.

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12.1 Introduction

Potassium (K) ranks third most important plant nutrients after nitrogen and phosphorus and seventh among all the elements in the earth crust. It plays a vital role in photosynthesis, starch-sugar interconversion, crop quality and also imparts disease resistance. Significant mining of soil nutrients though crop removal under fast growing modern agriculture leads to decline in soil nutrient status. The condition in case of K is more alarming where most of the farmers' practices involve only application of nitrogen and phosphorus which leads to K imbalance in soil. In recent years, it has been reported that application of K fertilizer responded well in K deficient soils. It is reported that the annual potassium removals through harvested crops in India are over 10 million tons (Mt) of K_2O, which clearly points to the soil K-depletion. Removal of K from soil in comparison to N and P is remarkably high in different copping systems particularly in those involving cereal and fodder crops. A huge K removal has been found by different crops (Table 12.1) without replenishment with K fertilizer or very low K replenishment as compared to the removal.

In general, total K reserves in most of the soils are in sufficient range. However, dynamics of different K pools is influenced by the presence of dominant soil minerals which ultimately determine the K availability in soil. It is reported that about 92–98% of soil K exists as part of mineral or structural-K and in a fixed or

Table 12.1 Potassium removal by major crops under field conditions

Groups	Crops	Biomass yield (t ha^{-1})	Total uptake (kg K ha^{-1})
Cereals	Rice (*Oryza sativa* L.)	5.14	180
	Wheat (*Triticum aestivum* L.)	3.90	137
Pulse	Chickpea (*Cicer arietinum* L.)	1.50	49
	Groundnut (*Arachis hypogaea*)	2.54	95
	Soybean (*Glycine max*)	2.50	101
	Alfalfa (*Medicago sativa* L.)	91.90	669
Oilseed	Mustard (*Brassica juncea*)	2.60	133
	Sunflower (*Helianthus annuus* L.)	2.38	141
Tuber	Potato (*Solanum tuberosum* L.)	29.50	119
Sugar	Sugarcane (*Saccharum officinarum* L.)	87.60	270
Fruits	Banana (Musa paradisiacal L.)	38.00	1053
	Pineapple (Ananas sativa)	84.00	440

Source: Tandon (1991)

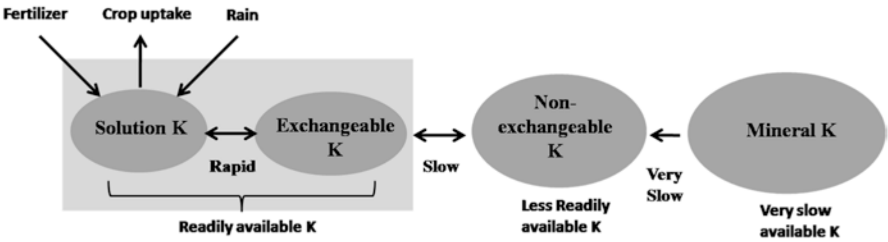

Fig. 12.1 Simplified K dynamics in the soil environment

non-exchangeable form of K (Basak et al. 2017). The sum of the solution K and exchangeable K is considered as 'readily available forms' which constitute about 1–2% of the total K in soil (Basak et al. 2017). Further, the share of the readily available forms present in soils is 98% in exchangeable and 2% in solution forms, respectively. However, all these forms are in dynamic equilibrium with each other (Fig. 12.1). It is evident that non-exchangeable K (also called as 'slowly available K') becomes available in soil when readily available K is depleted due to plant uptake (Sharpley 1989). For maintaining optimum level of K in the soil solution, it needs to be replenished by exchangeable K from clay minerals. For optimum K nutrition in plant, the soil solution has to be replenished instantly either by releasing K from non-exchangeable sources or by application of K-fertilizers (Basak et al. 2017).

Potassium bearing minerals are limited and finite resource in few selected counties. To meet the requirement of potash fertilizer in developing countries, the K fertilizer production needs to be increased by 2 times to sustain soil K level (Manning 2010).

Most of the K ores suitable for commercial K fertilizer production are distributed in few countries in the northern hemisphere (Canada, Russia, Belarus and Germany) and control more than 70% of the existing potash market. In terms of consumption patterns, it is in the order of East Asia ˃ Latin America ˃ South Asia ˃ Africa; where no significant K ore deposit is available for commercial K fertilizer production (FAO 2015). Therefore, the developing countries have left with no option to be independent in K-nutrition through commercial K fertilizer. These necessitate the need for finding some substitute of conventional K source for crop nutrition as well as maintaining the soil K status. The alternative of expensive imported fertilizers is to exploit indigenous and locally available low-grade K sources. The major source of K for plant nutrition comes from K-bearing minerals in natural condition (Biswas and Basak 2013a). Thus, use of such minerals is meaningful for increasing the yield and quality of crops as well as reducing the dependency of costly K fertilizers in agriculture. It is also very important to study the bio-activation of naturally occurring K-bearing minerals, their potentiality as K fertilizers and scope in sustainable crop production. In this chapter, we have discussed the indigenous K-bearing minerals, natural sources of K, and K mobilizing microbes and their scope in sustainable crop production.

12.2 Mineral Source of K

Potassium in soil is mainly present as minerals known as K-bearing minerals. The K supplying capacity of soil is mainly governed by the kind and content of minerals present in the soil as well as the rate of release in to available froms. In general, more than 90% of the total K in the soils is found in mineral forms or as structural K. Though mineral K is not directly available to plants but the availability depends on dynamics of other soil K pools (Sparks and Huang 1985; Sparks 1987). The primary sources of K-bearing minerals in soils are feldspars, micas (muscovite, biotite and phlogopite), zeolite, glauconite, potassium-taranakite, illite, vermiculite and chlorite (Basak et al. 2017). The commercial K fertilizers are manufactured from several minerals which are rich in K. The most important K minerals are sedimentary in origin and found either as chloride or sulfate forms. The minerals which are commonly used for commercial manufacture of K fertilizers are limited to sylvite, carnallite, langbeinite, nitre, polyhalite and kainite. Of these, sylvite and carnallite account for the majority of the production.

12.3 Naturally Occurring K-rich Salts

The principal sources of K around the world are clay minerals in soils and rocks, and salt deposits in the ocean in the process of crystallization of K salts in dried sea. K-bearing salts, particularly chloride, sulfate and nitrate, produced from natural salt pans are water soluble in nature. Majority of K fertilizers used in crop production are derived from deposits of marine salts in the process of evaporation. The following naturally occurring K salts are generally not used for commercial K fertilizer production, but can be utilized as alternative options of K for agricultural production.

12.3.1 Potassium Sulfate

Potassium sulfate (K_2SO_4) also known as sulfate of potash or arcanite is commonly used as the source potassium and sulfur in agricultural production. Only the naturally occurring potassium sulfate after mining can be used in agricultural production. No further processing is allowed after mining except crushing and sieving. In some European countries, special permission is required from the certifying body before application in soil. It is an inexpensive material that contains approximately 40% K_2O and 17% sulfur (Mikkelsen 2008). Due to its high water solubility, it is recommended to apply within crop growth period, otherwise it will washout through leaching (Sideman 2007).

12.3.2 Langbeinite (Sulfate of Potash-Magnesia)

Langbeinite mineral is a combination of two salts, i.e. potassium sulfate (K_2SO_4) and magnesium sulfate ($MgSO_4$) and also known as sulfate of potash-magnesia. There are many sources of the mineral and mainly distributed in North America particularly in New Mexico as underground deposits (Mikkelsen 2008). It is considered as an excellent source of potassium for organic agricultural production and several approved products are available in the market. Only raw langbeinite after crushing and sieving is allowed in organic agriculture which contains 18% K, 11% Mg and 22% S. The mineral is popularly known as *Sul-Po-Mag* and considered as the most cost-effective source of potassium for organic agriculture. The potassium in *Sul-Po-Mag* is immediately available to plants and can be used only when the crop is growing.

12.3.3 Magnesia-Kainite

Magnesia-kainite is a crude potash salt mined from natural deposit in Europe. It was formed by the evaporation of seawater many millions of years ago, and contains the valuable mineral kieserite. Apart from K, it also contains magnesium, sodium, and particularly it is a cost-effective fertilizer suitable for application to grassland, forage crops and sugar beet. Nutrients are immediately available to crops as they are 100% water soluble and unaffected by the soil pH and therefore suitable for use in all soil types. It is a unique K fertilizer because it is balanced with sodium and magnesium to reduce the risk of metabolic disorders in livestocks. So, application of magnesia-kainite in the pastureland has a direct and measurable effect on the mineral content of the forage. Due to its natural origin and the minimal processing in the fertilizer factories, magnesia-kainite is suitable for organic farming according to the regulation and also has been certified by the Soil Association the United Kingdom for use in organic farming systems.

12.4 Potassium in Silicate Minerals

Weathering of silicate minerals and mineralization of organic residues are main source of K for plant growing under natural conditions. Potassium bearing minerals such as feldspar, leucite, mica, glauconite and K rich clays are the K reserve in soils. Potassium availability is a critical factor in developing countries dominated by highly weathered soils like oxisols and alfisols. These soils are inherently deficient in K reserve and do not provide responses to application of water soluble K fertilizer due to an intensive leaching under exhaustive cropping systems. So, naturally occurring locally available geological deposits of low-grade K minerals may be considered under this situation. These unconventional sources do not provide readily available K like commercial water soluble fertilizers. However, these sources may release sufficient amount of K to provide agronomic benefits and can be more effective than commercial fertilizer in highly weathered soil under intensive leaching.

Table 12.2 List of potassium bearing silicate minerals, their composition and per cent K_2O

Name of potassium minerals	Composition	K_2O (%)
Leucite	$KAl(SiO_3)_2$	21.4
Feldspars:		
Orthoclase	$KalSi_3O_8$	16.8
Anorthoclase	$(Na, K)AlSi_3O_8$	2.4–12.1
Microcline	$KAlSi_2O^3$	16.8
Micas:		
Muscovite	$H_2KAl_3(SiO_4)_3$	11.8
Biotite	$(H, K)_2(Mg, Fe)_2Al_2(SiO_4)_2$	6.2–10.1
Phlogopite	$(H, K, Mg, F)_3(Mg_3Al(SiO_4)_2$	7.8–10.4
Lepidolite	$KLi(Al,OH,F_2)Al(SiO_3)_3$	10.7–12.3

Source: Sauchell (1961)

Considering their worldwide availability and agronomic benefits, there is no other opinion that indigenous silicate minerals are an alternative option of K source in the developing countries. The major K-bearing silicate minerals are listed in Table 12.2.

Several attempts have been made to address the issue of different potassium silicate minerals as a source of K and their agronomic efficiency under pot trial and field conditions (Coreonos et al. 1996; Hinsinger et al. 1996; Yao et al. 2003). Both greenhouse and field trials were conducted in order to work out the efficiency of the minerals as the source of K for crop growth. The agronomic effectiveness of K-bearing minerals is largely determined by their mineralogy and chemical composition. Agronomic effectiveness is also greatly influenced by the plant species and soil types. Among several plant species investigated, the utilization of K from gneiss followed the order: maize > ryegrass > alfalfa, and a greater uptake was possible from finer sized particles (Wang et al. 2000). So, type of plants and their root architecture played a vital role in releasing K from minerals. These minerals might be effective K suppliers in highly weathered soils where the use efficiency of chemical fertilizer is very low. For example, application of K-feldspar served as an effective substitute of muriate of potash (MOP) in Colombia, by considering the problem of KCl (MOP) use in highly weathered oxisols as well as agro-economic conditions (Sanz-Scovino and Rowell 1988; Wang et al. 2000). Initial soil K status also influenced the effectiveness of the minerals and their application is quite effective particularly in K deficient soils. It was reported that application of silicate minerals (fedspar, mica) improved plant biological yield and K uptake in spring barley (Madaras et al. 2013) and leek (Mohammed et al. 2013) under greenhouse condition. The mineral source of K was effective in some long duration crops like grape, coffee and olive. Berry yield K content in grape increased when biotite was used as a source of K in vineyard (Stamford et al. 2011), while phonolite was as effective as KCl in increasing fruit yield in coffee (Mancuso et al. 2014). These studies indicated that plant species along with their growth pattern also have significant role in releasing K from silicate minerals.

12.5 Greensand

Greensand is mainly consisted of glauconite mineral that does not behave like sand and has quite similarity with micas, particularly muscovite-illite like clay minerals. The minerals are largely deposited in the USA particularly in New Jersey and some parts of Delaware, Maryland and Virginia. Greensand is also found in India and distributed in some parts of Madhya Pradesh, Uttar Pradesh and Gujarat. The name itself represents the color (olive green) having high micro-pores as well as cation exchange capacity (20–30 cmol (p^+) kg^{-1}). It is also a predominant source of K along with calcium (Ca), magnesium (Mg) and micronutrients. The physical and chemical characteristics represent its potentiality as a nutrient source as well as soil amendment. Over 100 years, greensand has been marketed as a natural K fertilizer and soil amendment due its K content (8% K_2O) and moisture retention capacity. Natural greensand is not pure glauconite and the K content ranges from 0.1 to 7% in commercial product available in the market. Most of the studies have indicated that greensand has limitation as a K fertilizer as it contains soluble K 0.1% of the total K present (Mikkelsen 2008). However, application of greensand was found to improve potato tuber yield by 16% under light texture soil poor in organic matter content (Heckman and Tedrow 2004). It can also be prescribed as a non-chemical source of K fertilizer in natural farming systems.

12.6 Straw and Crop Residues

There are several options for the utilization of crop residues, however, recycling as the source of nutrients and organic matter has special importance in agriculture and environment. Straw and crop residues, particularly the cereal crop residues, generally contain a significant amount of K which can be effectively recycled as the source of nutrients. In case of grain crops, 50–75% of the total biomass is left as residue after harvesting. Every year India produces around 500 Mt agricultural wastes out of which 70% contribution comes from cereal crops (352 Mt). The crop residue production is increasing with the increase in area and production of cereals, particularly rice and wheat. Crop residues are the major source of organic matter (40% C of the total dry matter) as well as contain different plant nutrients which can be effectively recycled in the agro-ecosystem. Typical amounts of K in rice and wheat straws at harvest are 12–17 kg and 9–11 kg ton^{-1}. However, K content in Indian rice straw is generally more (up to 25 kg ton^{-1}) than other parts of the world (Singh and Sidhu 2014). The K contents in different crop residues and straws are presented in Table 12.3. There are many options through which the crop residues can be used as potassium sources: direct residue incorporation, composting and making ash or biochar (Singh and Sidhu 2014). The ash or biochar derived from crop residues has a significant amount K in readily available form and advantageous over other organic sources from the K availability point of view. It is also cost-effective to apply ash or biochar blended with organic manures in suitable proportion when a huge amount of waste disposal is a problem (Adeoye et al. 2001). Thus, proper

Table 12.3 Potassium content in different farm wastes (% dry weight basis)

Waste type	K content
Rice straw	1.75
Wheat straw	1.00
Alfalfa hay	2.20
Kentucky blue grass hay	2.00
Oat straw	1.50
Corn stalk	0.90
Sugarcane bagasse	1.20
Water hyacinth	2.20
Tobacco stems	7.00
Farm ash[a]	7.17

[a]Ash basis

Table 12.4 Potassium content in manures and composts (% dry weight basis)

Manures and compost	K content
Cattle manures	0.5–2.0
Chicken manures	1.5–3.0
Goat manures	1.0–2.8
Pig manures	0.5–1.2
Sheep manures	0.7–1.7
Rye green manure	1.8–2.1
Cowpea green manure	3.2–3.5
Composts	1.0–2.0

utilization of such farm wastes by converting them into valuable by-products (ash or biochar) have greater advantages over composting and direct application.

12.7 Manures and Composts

The manures and composts are generally applied to build up soil organic matter and to supply plant nutrients. The supply of nutrients from manures and composts occur slowly but continuously over the period of time. A wide range K concentrations was found in manures and composts since the source of raw materials and methods of preparation are highly variable (Hue and Silva 2000). There are some restrictions from certifying agencies on the use of immature manures, but well-matured composted materials are allowed as a source of nutrients (Hue 1995) The potassium content in different manures and composts are given in Table 12.4 as a base information. Due to a large variation in K contents, it is always advisable to analyze the K content before application to get the maximum benefit out of it (Nick and Bradley 1994). So, it is very important to study and identify the source of raw materials because the method of preparation does not add any nutrient in it.

12.8 Wood Ash

Wood ashes are one of the chief and well-known sources of K conventionally used in field crops, horticulture and forestry.

It is one of the ancient sources of K used to apply for building up the soil fertility. Apart from K source, it is also used as a soil amendment. Due to the presence of a significant amount of carbonate and oxides of alkali metals, it can correct soil acidity (Górecka et al. 2006). However, the importance of wood ashes in agriculture is mostly determined by the K content which varies from 5 to 7% (Hue and Silva 2000). The K content in wood ashes depends on the age of the wood; more is the age, higher is the K content. The whole K is water soluble in nature. So, it is recommended to apply just before the crop need to avoid leaching loss (Perry 1982).

12.9 Seaweeds

Seaweeds are multicellular algae commonly harvested from the sea. They have strong affinity for nutrients due to the high photosynthesis rate. Seaweeds can accumulate a significant amount of K because on an average 0.4 g L^{-1} K is present in the seawater. The seaweed biomass can be used directly as a natural K fertilizer as it contains on an average 2% K in readily available form (Hue and Silva 2000). Generally agricultural fields are far away from the seaweed harvesting area (sea coast). So, soluble K can be extracted from seaweed biomasses and used as a liquid organic K fertilizer to avoid the huge transportation cost. Among the seaweeds, Kelp is a promising marine algae used as organic sources of macro as well as micro-nutrients. It contains a significant amount of potassium (3–10% on dry weight basis) which is readily available to plants (Mikkelsen 2008). Seaweeds are an excellent source of organic matter that decompose quickly and release variety of nutrients in soil.

12.10 Potassium Biofertilizer

There are some bio-agents which can mobilize K from the structure of K-bearing minerals into available forms. These bio-agents are quite efficient in releasing K, particularly from silicate minerals, by producing low molecular weight organic acids (Biswas and Basak 2013b; Basak et al. 2017). These bio-agents mainly include bacteria popularly known as K-solubilizing microorganisms (KSM). Potassium solubilizing bacteria (KSB) is also known as biological potassium fertilizer (BPF). The BPF is quite popular in China and South Korea where it is used as K biofertilizer to mobilize native soil K due to the shortage of commercial K fertilizers (Sheng et al. 2002; Lin et al. 2002; Sheng and He 2006). In this way, KSB plays a vital role in the conversion of native soil K into readily available forms for plant uptake. The most important KSB used as K biofertilizers are *Bacillus mucilaginosus, Bacillus edaphicus, Bacillus circulans* and *Bacillus cereus*. There is still very little research about KSB as compared to N fixer and P solubilizer. Earlier, application of

Table 12.5 Important KSB and their effect on crop growth, yield and soil fertility

KSB	Experiment	Crop growth and yield	Reference
Bacillus edaphicus	Pot culture	Dry matter yield and K content increased in cotton and rapeseed	Sheng (2005)
Co-inoculation of *Bacillus mucilaginosus* (KSB) and *Bacillus megatherium* (PSB)	Pot culture	Increased K status in soil. Enhanced growth and NPK uptake by eggplant	Han and Lee (2005)
Bacillus cereus	Pot culture	Yield and K uptake increased in Sorghum while K status in soil improved	Badr et al. (2006)
Bacillus mucilaginosus	Pot culture	Improved K status and yield and K content increased in groundnut and Sudan grass	Sugumaran and Janarthanam, (2007), Basak and Biswas (2009, 2010)
Bacillus cereus	Field study	Increased yield and improved K use efficiency in tomato	Badr (2006)
Bacillus mucilaginosus	Field study	Increased biomass and fruit yield in hot pepper and K availability in soil	Supanjani et al. (2006)

potassium bearing minerals alone did not respond well as a source of potassium because most of the K is present in unavailable forms for plant uptake (Biswas and Basak 2014). Some of the recent findings indicate that the treatment of soils as well as potassium bearing minerals with KSB inoculation significantly increases soil K as well as plant growth (Basak and Biswas 2012; Basak et al. 2015; Basak et al. 2017). Therefore, some of the crops like wheat, sorghum, cotton, rapeseed, tomato and eggplant have been inoculated with KSB biofertilizers and found successful in increasing soil K status, crop growth and yield under pot culture as well as field conditions (Table 12.5).

12.11 Conclusions

Potassium is one of the key major nutrient elements for sustaining crop production, but the raw materials which are needed to manufacture K fertilizers are limiting in many parts of the world including in India. Therefore, research on finding alternative sources of K nutrition in crop fields is inevitable. Existing literature show encouraging results for the utilization of natural mineral and biological waste based K sources in agriculture. However, these results are limited mostly in laboratory based investigations. Few examples have been demonstrated under field conditions and in organic agriculture. Since the response of crops to alternative sources of K could highly depend on numerous soil and crop parameters and climatic conditions, long term field scale trials are immediately needed to work out the best possible alternative source specific to particular crop. Emphasis should be given on the utilization of biological entities such as crop wastes and biofertilizer in improving the nutrient use efficiency of plants. Since the multiscale benefits of biochar have already been extensively demonstrated in crop agriculture and soil carbon sequestration, production of biochar from K rich crop residues can be a novel technological advancement in tackling the K nutrition issue in Indian soils. Biochar could also be prepared with K-rich mineral supplements which might further increase the K content and release rate in soils. Bio-intervention (microbes and composting) of K-bearing minerals might be a promising approach for utilization of natural source of K in crop production (Basak et al. 2017). The new technologies should be trialed under various cropping systems, especially in orchard based crops, under diverse climatic conditions.

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Changes in Soil–Plant–Microbes Interactions in Anticipated Climatic Change Conditions

13

Pratap Bhattacharyya, Koushik Singha Roy, and Suvadip Neogi

Abstract

Ongoing global climate changes caused by human induced greenhouse gases (GHGs) represent one of the biggest problems in the twenty-first century. Terrestrial ecosystems play a major role in such climate change feedbacks because they release and absorb greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) while storing large quantities of carbon (C) in living vegetation and soils, thereby acting as a significant global C sink. The influence of climate change on the soil C sink remains a major area of uncertainty, especially as there is scope for warming induced liberation of CO_2 from soil to atmosphere due to enhanced microbial decomposition. The consequences of increased C flux from roots to soil for microbial communities and C exchange are difficult to predict, because they will vary substantially with factors such as plant identity, soil-food-web interactions, soil fertility and a range of other ecosystem properties. The interrelationship of soil microbes and C exchange include: (1) increases in soil C loss by respiration and as dissolved organic C due to stimulation of microbial abundance and activity; (2) stimulation of microbial biomass and immobilization of soil N, thereby limiting N availability to plants, creating a negative feedback that constrains future increases in plant growth and C transfer to soil; and (3) increased plant-microbial competition for N, leading to reduced soil N availability and microbial activity and suppression of microbial decomposition leading to increased C accumulation. In this chapter we will assess the complex interactions among plant, soil and microorganisms that influence climate change scenario.

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Greenhouse gas • Agriculture • Microorganisms • Carbon • Rhizodeposition • Enzymes

13.1 Introduction

Increasing trend in emissions of greenhouse gases (GHGs) is one of the key drivers of global climate change. Of course, the global climate change is likely to affect agro-ecosystems in many ways. The shift in agriculture productivity depends on the combined effects of climate (temperature, precipitation, elevated CO_2, extreme events, O_3, moisture stress) and other global change factors. Changes in agricultural productivity can be the result of direct effects of these factors at the plant level, or indirect effects at the system level, for instance, through shifts in nutrient cycling, soil–plant–microbes interactions, insect pest occurrence, and plant diseases.

The atmospheric concentration of carbon dioxide (CO_2) has increased from 270 μmol mol^{-1} to 398 μmol mol^{-1} as a result of rapid industrialization and coupled with several anthropogenic activities (http://weatherdem.wordpress.com). The major GHGs including CO_2, methane (CH_4), and nitrous oxide (N_2O) are the outcome of man-made activities and influence global temperature, climatic variables, and weather elements. As per the recent projection in the increase in atmospheric CO_2 concentration and air temperature would be 550 μmol mol^{-1} and 2 °C, respectively, by 2050 due to current scenario of industrialization and urbanization. Apart from these the elevated atmospheric CO_2 and other greenhouse gases may pose threat to global food supply by imposing negative effect on cereals production. As per the findings of Lele (2010) the rise in 2 °C in mean air temperature there would be profuse loss in crop yield (20–40%) and would be mostly observed in the countries of Asia and Africa. On the other hand, an average annual increase in grain production of 44 million tonnes is required to meet the food demands of the world by 2050 (Tester and Langridge 2010).

In the context of plant kingdom, C_3 crops are blessed with the CO_2 fertilization effect including stimulation in yield, improved nutrient-use efficiency, and much more as compared to that of C_4 plant species. However, this positive effect of CO_2 fertilization would become lessened coupling with warmer condition or high air temperature. The atmospheric warming accelerates plant development increases spikelet infertility as well, reduces nutrient-use efficiency but increases crop water requirement, lead to develop antagonistic relationship among the soil micro-flora. Moreover, climate warming disturbs the synchrony between temperature and photoperiod; because of this plants and microbes show individualistic responses to temperature, CO_2, and photoperiod, it is expected that climate change will affect the temporal and spatial functioning of soil–plant–microbes interaction.

As per the soil system is concerned, soil organic carbon (SOC) is considered as the major carbon (C) pool that behaves either as a sink or source of atmospheric gaseous-C. On growing pattern of climate changes are anticipated to regulate C exchange between soil, vegetation, and atmosphere. Direct effects would enhance

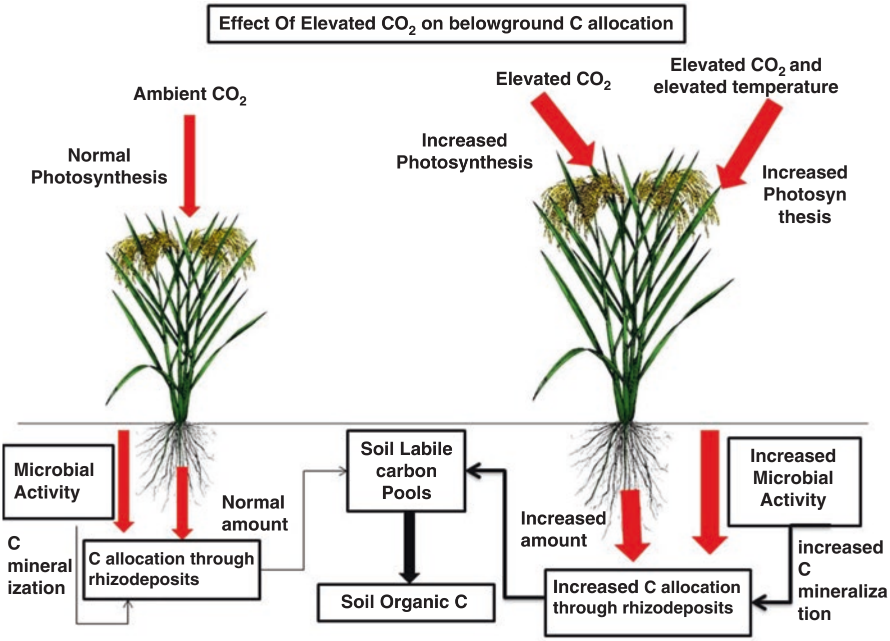

Fig. 13.1 Plant–soil–microbes interaction under anticipated climate changed scenario

respiration and mineralization of soil organic-C that brings in positive feedback to climate change. The beneficial effect of soil organic-C is more than improving soil quality and fertility. The climate effect can be moderated through C-sequestration. In general Soil C pool is about 3 and 4 times as large as the C content in the atmosphere and terrestrial biosphere, respectively (Lal 2004). Therefore, a minute change in soil C content could bring in significant sequestration of CO_2. Under CO_2 enriched environment, plant photosynthesis increases and a portion of the photosynthate becomes allocated to the belowground components. There is growing evidence for enhanced C input to soil through the root system under elevated CO_2 (Norby et al. 2004), which has the capacity to alter the biomass, diversity, and activity of soil microorganisms (Treseder et al. 2003). The basic mechanism of plant–soil–microbe interaction under elevated CO_2 could be presented in a flow chart cited below (Fig. 13.1).

Carbon and nitrogen (N) are key nutrients to plant physiological functions and soil microbial metabolism. The effects of elevated CO_2 and increased atmospheric temperature have critical impact on ecosystem functioning of today and future in the context of terms of C and N decomposition. It is anticipated that the allocations of C and N would be altered under elevated CO_2 as well as elevated CO_2+ temperature in accordance to the dry matter production and C and N concentration. The response of rice on C and N assimilation to elevated CO_2 can be elucidated through Fig. 13.2.

On the other hand, the large spatial heterogeneity of soil organic matter (SOM) restricts the detection of small increases in soil C content under elevated CO_2 (Taneva et al. 2006). The mechanisms involved in the storage, transformation, and

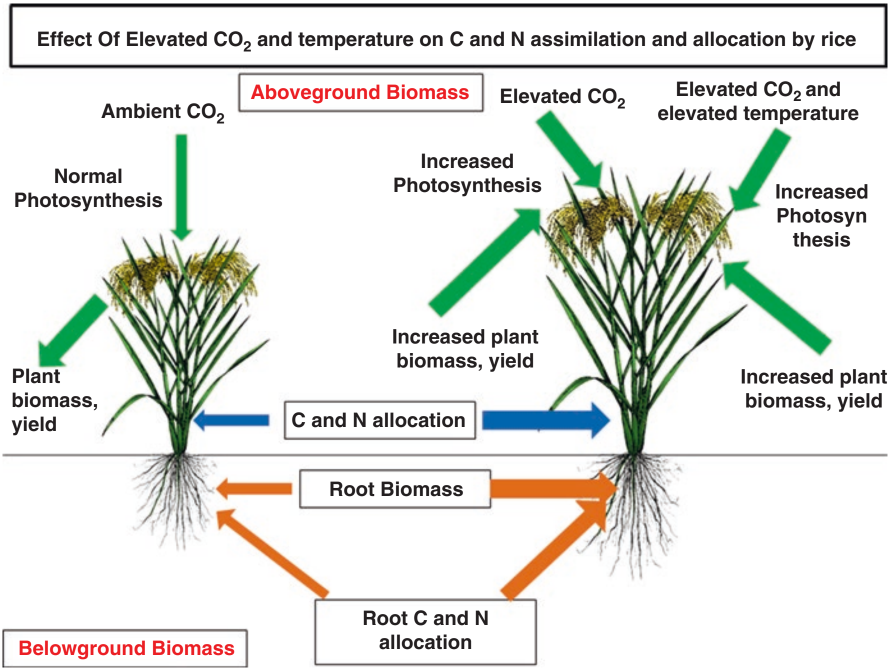

Fig. 13.2 Plant response to anticipatory climate changed scenario

turnover of C are not very clear. The labile C fractions in soil depend upon the soil type and nutrients availability and this condition becomes aggravated under elevated CO_2. The structural and functional diversities of soil microorganism regulate nutrient cycling and maintain soil health. Soil enzymes are the key drivers of functioning of soil microbial activities.

Soil microbial biomass (MBC) regulates nutrient cycling, soil health and determines ecosystem productivity (Marcel et al. 2008). Microbial biomass C controls belowground processes under elevated CO_2 found a significant increase in MBC under high CO_2 in submerged paddy soil. Elevated CO_2 also influence N cycle and increase microbial denitrification and emission of N_2O from soil. So there is urgent need to understand the detail soil–plant–microbes interaction under changed climate scenario in order to minimize the adverse impact of climate change on terrestrial ecosystem.

13.2 Relationship Among Soil–Plant–Microbe

Terrestrial ecosystems play a major role in such climate change-feedbacks because they release and absorb GHGs while storing large quantities of C in living vegetation and soils and act as a significant global C sink (Friedlingstein et al. 2006; Heimann and Reichstein 2008). The microbial communities and their exchange of

C vary substantially across ecosystems (Van der Heijden et al. 2008) that change in C input into soil. Plant-mediated indirect effects of climate change on soil microbes operate through variety of mechanisms (Johnson et al. 2005). The first mechanism explains that elevated concentration of atmospheric CO_2 brings in increased plant photosynthesis and transfer of photosynthate C belowground and soil micro-flora (Bardgett et al. 2005; Hogberg and Read 2006; Keel et al. 2006).

The interrelationship of soil microbes and C exchange include: (1) increases in soil C loss by respiration and other related activities (Heath et al. 2005; Bernhardt et al. 2006), (2) stimulation of microbial biomass and immobilization of soil N, and (3) increased plant-microbial competition for N (Hu et al. 2001). It is well established that climate change, especially warming and altered precipitation regimes, has the potential to alter the distribution of plant species and functional groups at both local and global scales (Woodward et al. 2004).

13.3 Impact of Changed Climate Condition on Functional and Structural Microbial Diversity

13.3.1 Soil Enzymes and Its Role in Terrestrial Ecosystem

Soil enzyme activity has been studied in relation to ecosystem responses to global change and decomposition of biopolymers (Finzi et al. 2006). The structural heterogeneity of biopolymers requires the interaction of several classes of enzymes to reduce them to constituent monomers available for microbial consumption (Sinsabaugh et al. 2002; Sinsabaugh 2005). The most widely assayed enzymes are those involved in the degradation of cellulose and lignin (Burns and Dick 2002). Apart from these enzymes, hydrolyze proteins, chitin, and peptidoglycan, which are the principal reservoirs of organic N (Caldwell 2005). Extracellular phosphatases are of interest for their role in mineralizing phosphorous (P) from nucleic acids, phospholipids, and other ester phosphates. Soil enzymes like β-glucosidase, invertase, and urease are primarily responsible for C and N transformation in soil.

There are three plant-mediated mechanisms by which elevated atmospheric CO_2 might influence soil enzymatic activities: (a) elevated atmospheric CO_2 stimulates plant photosynthesis, thus allocating photosynthate in below-ground processes (b) the alteration in soil C: N ratio, and (c) elevated atmospheric CO_2 reduces the stomatal conductance of plants which results in higher water use efficiency.

13.3.2 Reaction Mechanisms of Soil Enzymes

Enzymes work as per its substrate specificity and attack specific components either between or within major nutrient pools. There are specific chemical forms based on structure and bonding within major nutrient types such as C, N, and P. The major forms of C are polysaccharides, lignin, and polymethylene. The bulk of organic N is thought to be in amide form, either as peptide or non-peptide C─N bonds and organic P occurs in either a mono or diester form.

The breakdown of litter is governed by the various cellulolytic enzymes like endo-cellulases and β-glucosidases. In respect of N cycle, substrate specificity can be based on hydrolysis of different amino acid groups. Release of ammonium from various non-peptide C─N bonds can also be measured for a variety of different substrates (Tabatabai et al. 2002). Mineralization of phosphate from organic esters can be resolved into phosphodiesterase and phosphomonoesterase activities, reflecting the use of tissue-based and soil organic phosphates pools, respectively. There are different reactions mechanisms are found among C and N dependent enzymes, where removal of terminal amino acids is caused by the selective enzyme binding to either the free amino or carboxy-end of the peptide.

13.3.3 Approaches to Interpreting Soil Enzymes as Functional Diversity

Functional diversity between nutrient resources could be based on specific enzyme activities against major C, N, and P constituents. Functional diversity within a nutrient group can be estimated by measuring cellulose, phenoloxidase, β-glucosidase for C; urease, protease, amidase for N, and phosphomono and diesterases for P. The functional diversity of soil enzymes has frequently been evaluated as differences in activities. Ratios between and within major C, N, and P processing enzymes can provide insight into the microbial community response to changing nutrient resources and the relative importance of different nutrients.

In N cycle, Sinsabaugh et al. (2002) had also showed that shifts in urease to protease ratio, which suggested major differences in the relative importance or availability of protein-N versus urea-N. In the P cycle, the changes in phosphodiesterase to phosphomonoesterase ratios suggest major differences in the organic phosphate pools being altered by nutrient management practices. Multivariate techniques have used to relate soil enzyme activities to microbial community structure and physiology (Nannipieri et al. 2002; Saiya-Cork et al. 2002).

13.3.4 Soil Enzymatic Activity Under Changed Climatic Scenario

The dehydrogenase activity is commonly used as an indicator of soil biological activity (Bhattacharyya et al. 2012a, b, 2013a, b, 2014; Bhattacharyya et al. 2016).

The β-glucosidase catalyzes the hydrolysis and biodegradation of various β-glucosides present in plant debris. The final product of hydrolysis is glucose, an important C energy source of life to microbes in the soil. There is considerable evidence suggesting that a significant fraction of enzyme activity measured in soil originates from abiotic enzymes (enzymes of biological origin no longer associated with living cells) excreted into the soil solution or immobilized enzymes of microbial origin absorbed to clays or humic colloids (Bhattacharyya et al. 2012a, b, 2013a, b, 2014). The activity of β-glucosidase is fundamental in liberating nutrients, reducing the molecular size and thus facilitating future microbial activities. Like other soil microbial activities, it has also been reported that the β-glucosidase activity increases under elevated CO_2 and temperature condition owing to the abundance of increased soil labile C content (Bhattacharyya et al. 2012a, b, 2013a, b, 2014).

Fluorescein diacetate is hydrolyzed by a number of different enzymes, such as proteases, lipases, and esterases. The fluorescein diacetate (3,6-diacetyl fluorescein (FDA)) hydrolysis technique, evaluating the potential activity of ester-cleaving enzymes can be used to measure total microbial activity in soils.

Urease activities in soils have received a lot of attention since it regulates N supply to plants after urea fertilization. The efficiency of urea has been reported as low due to substantial N lost to the atmosphere through volatilization, a process mediated by urease. Studies have shown that extracellular urease associated with soil organo-mineral complexes is more stable than urease in the soil solution and those humus-urease complexes extracted from soil are highly resistant to denaturing agents such as extreme temperatures and proteolytic enzymes (Yang et al. 2006, 2007). Rapid hydrolysis of urea in soils due to urease activity leads to accumulation of ammonium. Significant increase in urease activity was reported at elevated CO_2 concentration and higher temperature (Niklaus et al. 2003).

Phosphatases are a broad group of enzymes that are capable of catalyzing hydrolysis of esters and anhydrides of phosphoric acid. In soil ecosystems, these enzymes play major role in P cycling as they are correlated to P stress and plant growth (Bhattacharyya et al. 2012a, b, 2013a, b, 2014). Land plants have evolved many morphological and enzymatic adaptations to tolerate low phosphate availability which tend to increase with high P stress (Li et al. 2002). Under the P deficiency condition in soil, acid phosphatase secretion from plant roots is increased to enhance the solubilization and remobilization of phosphate, thus influencing the ability of the plant to cope with P-stressed conditions (Versaw and Harrison 2002).

13.3.5 Impact of Climate Change on Soil Microbial Populations

Climate change associated is now accepted as a serious challenge to global ecosystems, but much is unknown about the extent of its impact on natural microbial communities. Microbial functions and activities may change as a result of the intensified anthropogenic activities. Therefore, belowground C allocation is governed through root exudation and turnover that change in size and activity of soil micro-flora (Hu et al. 2001; Rillig et al. 2001). The total heterotrophic bacteria, ammonia-oxidizing, nitrate oxidizing bacteria in soil were reported to be moderately and highly affected by anticipated climate change conditions (Horz et al. 2004).

There was no general tendency found to the response of rhizospheric microorganisms under high CO_2 conditions (Zak et al. 2000). An increase in bacterial population was observed in pastures ecosystem (Hu et al. 2001). However, Montealegre et al. (2000) did not detect any effect of CO_2 increase on bacterial community in the rhizosphere soil.

An increase in heterotrophic bacterial population under elevated CO_2 was observed by Hodge et al. (1998) in the rhizosphere of tropical soil. Tarnawski and Aragno (2006) noticed that under elevated CO_2 conditions, fast-growing microbial species which are adapted to feed on easily utilizable substrates are favored.

13.4 Influence of Anticipated Climatic Change Conditions on Soil–Plant–Microbes Interaction

13.4.1 Effect of Elevated CO_2 on C–N–Water Interactions in Soil

Carbon and N are critical to many aspects of plant, herbivore, and microbial metabolism. Elevated CO_2 could alter the C─N interactions in soil associated with microbial functioning which is also affected by rhizodeposition and root biomass and vice versa. If plants experience multiple resource limitations, interactions of CO_2 and N supply could limit the CO_2 fertilization effect on biomass and C accumulation. These interactions occur at eco-physiological to ecosystem scales, and involve plant–microbial, plant–consumer, and plant–plant interactions, or all of these. However, responses to elevated CO_2 are higher when N supply is high rather than low. We can also put it in this way that elevated CO_2 could progressively reduce the net N supply capacity of soil or causes N limitation, termed as progressive N limitation, which may further suppressing biomass at elevated CO_2. Climate warming and elevated CO_2 could interactively alter plant and soil N cycling, which in turn could influence response to elevated CO_2. Temperature has both direct physiological and indirect biogeochemical impacts on tissue-N concentrations. In cold regions, warming often increases leaf N concentrations because of enhanced soil N mineralization whether, a warmer region though, the initial stimulation of N mineralization by warming disappeared quickly resulting in progressively larger decreases in green leaf N concentrations over time. However, whether interactive effects of elevated CO_2 and temperature on C and N dynamics are common or consistent requires further study, especially for long-term processes (Reich et al. 2006).

Further, spatial and temporal variation in water availability has been played a vital role in regulating the effect of CO_2 fertilization. We can say, elevated CO_2 does often slightly increase soil water, and higher soil water is usually associated with higher rates of net N mineralization, so moister conditions could ameliorate both the synergistic CO_2–N interactions and progressive N limitation. However, this effect will likely occur only in systems where water and N co-limit plant production, because the interaction requires a convergence of N-limited growth and water-limited soil activity.

13.4.2 Effect of Elevated CO_2 and Temperature on Dry Matter Production and Aboveground C─N Allocation

As per the study of Roy et al. (2012) the highest rate of dry matter production (87.1%) in the aboveground portion was noted under elevated CO_2 and temperature

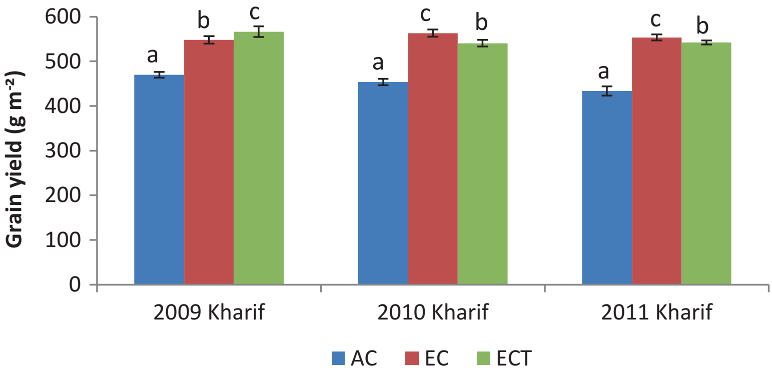

Fig. 13.3 Grain yield under ambient CO_2 (AC), elevated CO_2 (EC), and elevated CO_2+ elevated temperature (ECT) in three *kharif* cropping season (2009–2011). The columns followed by a common letter in a particular growth stage are not significantly ($p < 0.05$) different by Tukey HSD test

at the panicle initiation stage over the period of three *kharif* cropping season. Root biomass, leaf area index (LAI), and net C assimilation rates (NAR) also increased significantly under EC by 28, 19, and 40%, respectively. The grain yield was significantly higher under elevated CO_2 compared to control (22.6%) (Fig. 13.3). The C concentrations in stem, leaves, and roots were highest at the heading stage and increased significantly by 5, 4.8, and 4.9% in stem, leaves, and roots, respectively, under elevated CO_2.

13.4.3 Effect of Elevated CO_2 and Temperature E on Grain Quality and C—N Allocation of Rice

The effect of CO_2 fertilization on biomass production, C and N concentration in plant parts, its allocation, and grain quality in a tropical rice (cultivar-Naveen) was studied for three years in dry cropping seasons (*rabi* season) (Roy et al. 2015). Aboveground dry matter, root biomass, LAI, and NAR increased significantly under elevated CO_2 by 32, 26, 21, and 37%, respectively (Table 13.1). The grain yield was also significantly higher under elevated CO_2 (21.6%), although the higher temperature significantly reduced the yield advantage by 8.5% than elevated CO_2. The amylose content was significantly increased by 10% under e-CO_2+T elevated CO_2.

13.4.4 Microbes Mediated N Fixation and Interactions with Plant and Other Nutrients Under Elevated CO_2

Symbiotic biological N_2 fixation often increases with elevated CO_2. Fixation of atmospheric N_2 requires reduced C, which higher rates of photosynthesis in response to *elevated* CO_2 can supply. Bacterial symbionts use this C surplus to fix N_2,

Table 13.1 Biomass and yield components of rice (*cvNaveen*) under elevated CO_2 and temperature in three *rabi* cropping seasons

Year (Y)	Treatment (T)	Tiller no (m^{-2})	Panicle no (m^{-2})	Fertile spikelet (m^{-2})	Above ground biomass (g m^{-2})	Root biomass (g m^{-2})	Grain yield (g m^{-2})
Year 2009–2010	UC	442a	391a	11733a	1035a	170a	473.1a
	CC	434a	386a	12053a	1024a	165a	469.2a
	e-CO_2	581b	478b	14946b	1197b	194b	565.1c
	e-CO_2+T	563b	472b	14441b	1213b	193b	519.4b
Year 2010–2011	UC	490a	436a	12486a	1019a	274a	476.2a
	CC	482a	426a	12543a	1027a	281a	453.3a
	e-CO_2	621b	515b	14888b	1204b	329b	562.1c
	e-CO_2+T	606b	503b	14718b	1186b	338b	515.2b
Year 2011–2012	UC	507a	464a	13053a	1075a	271a	474.5a
	CC	500a	452a	13227a	1064a	266a	461.3a
	e-CO_2	620b	558b	16017b	1280b	319b	556.3c
	e-CO_2+T	613b	544b	15739b	1281b	322b	513.2b

Note: In each column values followed by different letters are significantly different in a given year by Tukey–Kramer's HSD test

providing needed N to the plants. Experimental evidence reveals that, where phosphorus (P), potassium (K), and/or other non-N nutrients have been added, N_2 fixation often shows a positive response to elevated CO_2 (van Groenigen et al. 2006). For example, in a long-term experiment of pasture receiving annual supplements of P, K, and magnesium (Mg), elevated CO_2 increased N_2 fixation (Lüscher et al. 2000). But in the absence of such nutritional supplements, N_2 fixation is often unresponsive to elevated CO_2. Moreover, elevated CO_2 can increase or decrease the relative abundance of N_2-fixing plants, suggesting that some of the effects of elevated CO_2 on N_2 fixation may be manifest as plant communities rather than changes in N_2 fixation on a per plant basis. For example, in the New Zealand FACE pasture experiment, legumes responded positively to elevated CO_2, constituting an increasing proportion of the total community biomass and productivity (Ross et al. 2004). In salt marsh, associative N_2 fixation increased after four months of elevated CO_2 (Dakora & Drake 2000), but in longer-term field experiments, elevated CO_2 did not appear to alter N_2 fixation by free living heterotrophs (Reich et al. 2006).

13.4.5 Changes of Rhizodeposition and Soil–Plant–Microbes Functioning Under Elevated CO_2 and Temperature

The changes of carbon allocation in soil–plant–microbes system were studied in tropical rice soil (Aeric Endoaquept) under elevated CO_2 and elevated CO_2+ elevated temperature conditions in field condition (Bhattacharyya et al. 2013b). There

Table 13.2 Total organic carbon in rice root exudates during various stages of crop growth under ambient CO_2, elevated CO_2, and elevated CO_2+ elevated temperature

	Total organic carbon in root exudates (mg C plant $^{-1}$ day $^{-1}$)				
Treatments	Maximum tillering	Panicle initiation	Grain filling	Harvesting stage	Seasonal mean
Ambient CO_2	89[a]	174[a]	80[a]	66[a]	102[a]
Chambered ambient CO_2	101[a]	188[a]	89[b]	79[b]	114[a]
Elevated CO_2	191[c]	191[b]	132[c]	104[c]	169[b]
Elevated CO_2 + Temperature	150[b]	230[b]	139[d]	115[d]	158[b]
L.S.D. (0.05): Treatment = 7.3; Stage = 7.3; Treatment × Stage = 14.					

Note: In each column values followed by different letters are significantly different in a given stage of plant growth by Tukey–Kramer's HSD test

were significant increase of root biomass by 39% and 44% under elevated CO_2 and elevated CO_2+ temperature compared to ambient condition, respectively. A significant increase (55%) of total organic carbon (TOC) in the root exudates under elevated CO_2+ temperature was noticed (Table 13.2.).

13.4.6 Net Ecosystem Production and Carbon Sequestration Under Elevated CO_2

Net ecosystem production (NEP), the sum of net primary production (NPP) minus total heterotrophic respiration, is one explicit measure of ecosystem C uptake. Plant biomass production is one key component of NEP, the larger elevated CO_2 enhancement of plant biomass with added N indicates the potential for added N to stimulate the response of NEP to elevated CO_2. Now, whether this potential is realized depends on how elevated CO_2 affects soil heterotrophic respiration from standing and soil surface detritus, and heterotrophic respiration from microbial breakdown of soil organic carbon stocks (van Groenigen et al. 2006). For an example, in the Swiss FACE pasture, mean soil C pools were higher with elevated CO_2, and the difference was slightly larger with added N; however, overall, changes in NEP due to elevated CO_2 in various experiments are apparently small on an annual basis and appear to exhibit little sensitivity to N additions. A synthesis that divided up data (total n = 80) from a broad array of indoor, open-top chamber, and FACE experiments into contrasting N fertilization levels suggests that soil C is insensitive to elevated CO_2 in the absence of N supplements and that exogenous N is needed for elevated CO_2 to increase soil carbon (van Groenigen et al. 2006).

13.4.7 GHGs Emission Under Elevated CO_2 and Temperature in Rice

Bhattacharyya et al. (2013a, b) studied on soil labile C and N pools, microbial populations, and enzymatic activities in relation to emissions of methane (CH_4) and nitrous oxide (N_2O) in a flooded alluvial soil planted with rice *cv* Naveen in open top chambers (OTCs) (Bhattacharyya et al. 2013a). The labile soil C pools, namely microbial biomass C, readily mineralizable C, water soluble carbohydrate C, and potassium permanganate oxidizable C were increased by 27, 23, 38, and 37%, respectively, under high CO_2. The total organic carbon (TOC) in root exudates was 28.9% higher under high CO_2. The labile N fractions were also increased significantly (29%) under high CO_2. Methanogens and denitrifier populations in rhizosphere were higher under high CO_2. As a result, CH_4 and N_2O─N emission were enhanced by 26 and 24.6%, respectively, under high CO_2.

13.4.8 Phosphorous Dynamics in Rice Soil Under Anticipated Climatic Change Conditions

The P uptake in relation to organic acid exudation from roots, microbial biomass P, and phosphatase activities was investigated by Bhattacharyya et al. (2014). Root exudates were analyzed at different growth stages of rice followed by organic acids determination in HPLC. Four different types of organic acids *viz.* acetic acid (AA), tartaric acid (TA), malic acid (MA), and citric acid (CA) were identified and quantified as dominant in root exudates, concentration of these was in the order of TA > MA > AA > CA. On contrary, the P use efficiency was significantly lowered under high CO_2. Soil MBP, acid, and alkaline phosphatase activity were significantly higher under elevated CO_2 by 35.1%, 27, and 36%, respectively.

13.4.9 Changes in Structural Microbial Diversities Under Elevated CO_2 and Temperature: A Metagenomics Approach

The whole genome metagenomic sequence data of lowland rice exhibited the dominance of bacterial communities including Proteobacteria, Firmicutes, Acidobacteria, Actinobacteria, and Planctomycetes. Interestingly, four genera related to methane production, namely *Methanobacterium, Methanosphaera, Methanothermus*, and *Methanothermococcus* were absent under high CO_2. The acetoclastic pathway was found as the predominant pathway for methanogenesis, whereas, the serine pathway was found as the principal metabolic pathway for CH_4 oxidation in lowland rice. The abundances of reads of enzymes in the acetoclastic methanogenesis pathway and serine pathways of methanotrophy were much higher under high CO_2 (328 and 182, respectively) (Bhattacharyya et al. 2016).

13.5 Conclusion

The enhanced C inputs under elevated CO_2 may be allocated to labile C pools that turn over rapidly and are not incorporated into stable SOM pools with long residence times, but may increase soil respiration rates. The mechanisms involved in the storage, transformation, and turnover of the additional C entering soils when ecosystems are exposed to elevated atmospheric CO_2 are not well understood, but are of critical importance to the accurate evaluation of the long-term storage capacity of soils for anthropogenic C. Soil C balance is a function of plant C inputs and C outputs through heterotrophic respiration. Increased C inputs to soils with elevated CO_2 have been hypothesized to lead to both soil C and nutrient accumulation and, in contrast, to greater soil C and N cycling rates and increased decomposition. Furthermore, there is increasing evidence that enhanced plant activity and belowground C inputs under elevated CO_2 can, directly or indirectly, lead to increases in SOM decomposition dynamics.

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Adaptive Soil Management: A Tool for Plant Fitness in Stressful Environment Through Microbial Integrity

14

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Abstract

Stresses are the potential threat to principal crop like rice, wheat, maize millets' productivity in all over the world. Events like continuous drought, torrential rains, flooding, heat waves, soil salinity, acidity, metal toxicity and frost damage have been experienced by agriculture. Incidence of invasive weeds as well as plant pathogenic microorganisms may further be increased in coming days due to anthropogenic perturbation and climate change phenomenon. Versatility in crop plant adaptation and appropriate management strategies are required to cope with such stressful condition. Evolving new crop varieties through breeding, screening and selection of potential crops from existing germplasms, crop improvement through biotechnological approaches and exogenous application of osmoprotectants, etc., are the possible mitigation options to be adopted. However, extent and rate of progress in this line is limited. More so, evolving stress tolerant crop varieties through classical and molecular techniques is time taking and consequently expensive. Benefits derived from molecular breeding are also much less uniform and detectable as they depend on microclimate. Current leads suggest gene based technology is not the appropriate approach to develop stress tolerant crop plant. Moreover, one of the potential problems associated with GM crops is that the novel gene might be unintentionally transferred by pollination or by horizontal gene transfer to weeds or soil-borne pathogens leading to the destabilization of the ecosystem. In this background, soil adaptive management strategies those restore the natural resources in soil and combat the abiotic and biotic stresses without hampering crop yield significantly and those impart the whole production system resistance against multiple stresses by exploiting microorganisms and their notable properties of ubiquity, adaptation to stressful

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environment, species richness and unique ways of interaction with crop plants will be attractive.

Building a resistant soil is a crucial element of adaptive soil management in helping farms to adapt themselves to harsh condition. Zero tillage/minimal tillage, cover crops and crop residues incorporation, crop rotation, organic husbandry, legume intercrops, biofertilizer, manure and compost application, site specific and problem oriented crop selection, adjustment in sowing/planting are some ways of adaptive soil management in building soil health resistant to stresses. These practices trigger specific microorganisms to be co-adapted with tolerant crop plants and elaborating biologically active metabolites for better retention of soil moisture and reduce erosion, decrease stresses as well as increase biodiversity in the system inducing better plant growth and thus, help in better stabilization of farm production and income.

Keywords
Abiotic and biotic stress • Microbial co-adaptation • Water smart • Salt smart • Acid smart • PGPR • Stress alleviation

14.1 Introduction

Principal crop productivity in the globe is impacted by abiotic stresses like drought, salinity, heat wave, acidity, nutrient deficiency or toxicity and flooding. Severity of these stresses is more pronounced in country like India, where they cause food and nutritional insecurity due to large population and poverty, especially in rural areas. Drought has severely restricted the cultivation of 33% arable land of India and further 35% is prone to such damage if rainfall is exceptionally low for extended period. While salinity, sodicity, acidity and nutrient deficiency or toxicity render more than 100 million hectares of agricultural land uncultivable thereby resulting in low crop production and consequently of nutritional and social insecurity. Thus, abiotic stresses emerge to be one of the important factors underlying poverty for millions of people. Ironically, those stress-affected areas are the ones where majority of poor people live and they have little bargaining capacity for costly agricultural inputs.

In this context, it is deemed necessary to evolve suitable technologies to ensure maximum crop production with assured profit from ecologically disturbed environment. Breeding of stress tolerant elite crop varieties, screening and identifying of potential stress tolerant crops as well as crop improvement through gene manipulation are the current leads to be adopted for successful harvest from stressful environment.

Classical breeding and trait based approaches are proven technologies for improving tolerance against stresses and thus, these areas have been focused for further research. However, success in developing stress tolerance in crop plant through classical breeding is meager. This is primarily due to intricacy in minor gene's expression responsible for stress tolerance. On the other hand, selection programme for searching out elite crop varieties is time consumable and expensive also. During the last decade, progress in the field of molecular technology for stress tolerance crop improvement has been recorded in few principal crops. With this progress, it is urged that future research priority should be directed towards stress tolerance related molecular, physiological and metabolic events for developing crops with and inherent capacity to cope with stresses.

But such vertical resistance may lose its implication under upcoming multiple stress environment. For example, drought tolerant crop plants can combat up to certain level of water-deficit conditions but then lose their potentiality as the severity of stress increases. Benefits derived from molecular breeding are also much less uniform and detectable as they depend on microclimate, rainfall and soil properties of the target environment. On the other hand, genetic engineering technology is not well suited for developing stress-resistant plants. Stress tolerance is a complex trait, often involving the interaction of many genes, and thus beyond the capability of a rudimentary technology based on high expression of few well-characterized genes. Moreover, one of the potential problems associated with GM crops is that the novel gene might be unintentionally transferred by pollination or by horizontal gene transfer to weeds or soil-borne pathogens. Such transfer could lead to the development of resistant super weed or super pathogens, i.e. genetically modified weed and pathogens those cannot be controlled by normal pesticides, and possibly the destabilization of the ecosystem.

Practical problem associated with such development is of overdependence on large seed companies and high seed price which compels the poor farmer to sink into debts further. More so, such varieties lack important traits required for sustaining under low input conservation agriculture. Thus, the poor people in stress vulnerable areas will be affected more and thus, require relatively affordable and easily available user-friendly technologies for cultivating crops even under stressful condition.

Under these backgrounds, conservation agriculture, an adaptive soil management, is the right choice in sustaining crop productivity under stressful environment. It is globally hypothesized that conservation agriculture restores the natural resources in soil and combats the stresses and thus, stabilizes the ecosystem with an option for optimizing yield with healthiest soil. Under conservation farming, the whole production system itself acquire resistance against multiple stresses either by revitalizing the soil ecosystem with rich biodiversity of keystone species, i.e. species that has a disproportionately large effect in its environment relative to it abundance, and their functioning that ensures lifeline activities of soil like mineralization, solubilization, fixation, antibiosis, symbiosis, etc., as well as important metabolic activities of plant even under stress or by developing horizontal crop resistance against different stresses through natural out crossing between the crop varieties generally used in low input conventional farming. Plant growth promoting rhizobacteria (PGPR) enhance crop tolerance to abiotic stresses by virtue of producing active biomolecules like growth promoting substances, siderophore, ACC diaminase enzyme for lowering plant ethylene directly and indirectly by controlling plant pathogens.

Crop diversity and healthy soils are prime to conservation agricultural practices to make farming system more resistant and resilient to erratic weather condition. Practices that trigger better retention of soil moisture and reduce erosion as well as increase biodiversity in the system induce better plant growth help in better stabilization of farm production and income.

Farmers now follow some management practices to build healthy soils. Zero tillage/minimal tillage that help in soil aggregate, cover crops that reduce moisture loss from soil and crop, crop residues, legume intercropping and composts those enrich soil organic matter are the adaptive management approaches to facilitate water holding capacity (WHC), water infiltration, nutrient availability and carbon-sequestration. Which, in turn, help the plant to stay fit under stressful environment.

Success of adaptive soil management to alleviate stresses relies on the co-adaptation of strong frontline multifaceted microbial guild. They extend necessary support to the crop by virtue of elaborating biologically active substances which, in turn, help the crop plant to survive under stressful situation. Efforts made so far in this direction are scarce and unexplored. Emphasis should be given on research and extension strategies to make the approach popular.

14.2 Soil Stresses and Related Impact on Soil Microbes

Stresses	Impact on soil microbes
Traffic load	Compaction, structural deterioration, habitat destruction, poor respiration, poor microbial load
Poor drainage	Soil wetness, poor aeration, low microbial activity, lower rate of nutrient transformation
Intensive cultivation	Structural aberration, habitat destruction, nutrient toxicity/deficiency, organic matter depletion, shift in microbial community, extinction of key stone microbial species, loss of biodiversity
Use of agrochemicals	Biological degradation, loss of biodiversity, shift in microbial community, microbial adaptation in new environment
Monoculturing	Poor biodiversity, lower substrate preference, preponderance of crop associated plant pathogenic organisms
Acidity	Aluminium toxicity, low rhizobial activity in low pH soil, activity of *Nitrosomonas* and *Nitrobacter* mediated nitrification inhibited at highly acidic soil, enzyme mediated biochemical transformations are also regulated by pH level of soil
Alkalinity	Negative effect with increasing alkalinity on the soil microbial community, biomass carbon, higher metabolic quotient

(continued)

Stresses	Impact on soil microbes
Drought/moisture stress	Cells succumb due to desiccation, reduced microbial growth, vegetative cells turn to resistant spores (e.g. bacteria) or resting structures (e.g. fungi), reduced enzyme activity
Salinity	Higher metabolic quotient, i.e. higher respiration to biomass ratio, physiologically more active population, high bio-energetic taxation, microbes suffer from osmotic stress, which results in drying and lysis of cells, lower microbial biomass
Metal toxicity	Reduced abundance of bacteria, fungi and actinomycetes, drastic reduction of free living N-fixing bacteria, dehydrogenase—highly sensitive, shift in microbial communities in long-term metal contaminated sites, high metabolic quotient, shows resistance against specific metals
Flooding	Shift in microbial communities adaptable more to anaerobic condition developed by flooding, negative effect on mycorrhizal fungi
Invasive organisms	Possible negative effect on native one, change in local genetical diversity, reduce biological buffering of niche, redistribution of invasive weed/plant associated pathogens, vulnerable to threatened microorganisms
Fire	Nitrifying bacteria, ecto and endo mycorrhizae drastically reduced, soil enzymes denatured

14.3 Microbial Integrity for Plant Fitness Under Compacted Soil

Intensification in agriculture has resulted from shortage of farm land and also for satisfying the need of an ever-growing population. In the pace of intensification, biological driven soil processes are modified and in most cases for better output form soil, excessive chemical and mechanical inputs are employed (Giller et al. 1997). Such substitution causes stresses associated soil physical degradation such as erosion and compaction. Compaction, a potent stressor, is due to heavy vehicular traffic in agricultural operation. This results in poor soil health. As a result, lifeline activities in ecosystem, sustainability in production system and ecosystem stability are hampered.

Heavy traffic load is a part and parcel of intensive agricultural production systems using power driven heavy agricultural machineries. This results in soil compaction—a potential stress to soil and its biological components and hence crop production decreases (Miransari 2014a, b). Under compaction, poor root growth restricts nutrient and water uptake, the rate of macropores decreases (Amato and Ritchie 2002). Decreased air circulation in compacted soil causes O_2 deficiency (Smith et al. 1989) and accumulates higher rate of CO_2. As a result crop performance is tremendously affected (Miransari 2014a, b). Pale leaf, stunted growth and poor root ramification are the distinguished signs of stress associated with soil compaction.

Different mitigation options are put forward to alleviate compaction related stresses on crop performance. Usually mechanical methods are not recommendable due to their high expenses and their adverse effects on the environment (Bergough et al. 2006). As mycorrhizal fungi are well adapted and survive in compacted zone use of such. Arbuscular mycorrhizal (AM) fungi have been tested and proved to be effective adaptive management approach to cope the crop plant even in high compaction due to heavy traffic load in agricultural field (Miransari 2009a, b).

It has been recorded that not all the AM fungi are well adapted in compaction zone of soil. *Glomus intraradices* establishes and elaborates beneficial effects by extending its mycelial network far from compacted zone for harvesting water and nutrients in their special structure called vesicle to provide nutrient, particularly, P and Zn to the plant even in high compaction. As compaction is unavoidable fate of intensive agriculture, crop fitness must be assured in the prevailing stress by adaptive soil management through compaction smart mycorrhizae.

14.4 Microbial Integrity for Plant Fitness Under Invasive Soil

Invasive soil is soil that has been accidentally or deliberately introduced by aggressive weeds and pathogens and threatens soil ecosystem. Invasion by annual grasses, soil-borne plant pathogens are major concerns of ecologists and resource managers for sustainable agriculture. Incidence of such event under the intensive agriculture and indiscriminating use of chemical inputs will be more in future due to excessive accumulation of reactive nutrient molecules with decreasing soil organic matter in degraded soil. Protection or re-establish functioning of desired crop communities against invasive weeds and pathogens depends on maintaining or improving ecosystem health by encouraging the microbial communities adapted under excessive nutrient accumulation, particularly of nitrogen. Invasive weeds and pathogens are opportunists. They can survive and flourish by exhausting whatever nutrients are there in soil. Microbes by virtue of their superiority in acquiring nutrient can modify invasion by weeds and pathogens in conducive soils for restoring desired plant communities.

Methods currently employed for arresting invasion by rangeland species are basically target oriented, i.e. treating invasive plants and pathogens of interest rather than manipulating of ecological processes that facilitate their invasion and disrupt natural successional dynamics (Hobbs and Humphries 1995; Sheley and Krueger-Mangold 2003; Sheley et al. 1996). Nitrogen management in crop field is an adaptive soil management for controlling invasive weed and pathogens (Vasquez et al. 2008). Increased nutrient availability can favour the invasion and success of invasive plant species in ecosystems (Ehrenfeld 2003; Norton et al. 2007; Sperry et al. 2006). Invasive weeds and plant pathogens are aggressive and flourish rapidly by using plant available nitrogen (PAN). A group of copiotrophic microorganisms, those favour nutrient rich condition, are adapted in rhizopshere of crop plants. They immobilize the reactive nitrogen molecule in their cell components in a competitive way. Thus, reducing the concentration of nitrogen in soil resists the dominance of invasive weeds or pathogens.

Invasion of soil-borne plant pathogens may be checked by creation invasion resistant soil through diseases suppression. In diseases suppressive soil numbers of microorganisms are adapted and extend frontline defense to crop plants. Organisms, operating in diseases suppressive soil, do so via multiple ways including competition for limiting nutrients, antibiosis, and triggering induced host resistance in crop plants of interest. In Fusarium wilt suppressive soil, non-pathogenic *Fusarium* spp. and fluorescent *Pseudomonas* spp., for example, are found to be operative. Suppression of take-all of wheat caused by *Gaeumannomyces graminis* var. *tritici* is basically due to the preponderance of fluorescent pseudomonads and their noble elaboration of antibiotic 2,4 diacetylphloroglucinol.

Organisms operative in pathogen suppression do so via diverse mechanisms including competition for nutrients, antibiosis and induction of host resistance. Non-pathogenic *Fusarium* spp. and fluorescent *Pseudomonas* spp. play a critical role in naturally occurring soils that are suppressive to Fusarium wilt. Suppression of take-all of wheat, caused by *Gaeumannomyces graminis* var. *tritici*, is induced in soil after continuous wheat monoculture and is attributed, in part, to selection of fluorescent pseudomonads with capacity to produce the antibiotic 2,4-diacetylphloroglucinol. Specific wheat varieties induce suppressiveness to Rhizoctonia root rot of apple in permanent orchard. Suppressiveness is primarily due to rhizosphere effect of wheat on specific fluorescent pseudomonads to augment their population and elaborate antibiotic to act on apple root rot pathogen *Rhizoctonia solani* AG 5 (Mazzola 2002). So, creation of suppressiveness soil is an adaptive soil management to control several soil-borne diseases.

Reduction in the intensity of disease caused by *Rhizoctonia solani* has also been reported in suppressive soil developed by long-term planting of specific host plant. This is attributed by increased abundance of *Trichoderma* spp. with their superior parasitism on *R. Solani*. This is the line with the observation of Henis et al. (1979) and this was further confirmed by Liu and Baker (1980) who identified *T. harzianum* as the potent suppressor of disease. Thus, the use of specific cropping sequence can elicit the desired shifts in microbial communities to check soil-borne plant pathogens

Certain antibiotic-producing fluorescent pseudomonads and parasitic fungi *Trichoderma* spp. (Cook and Rovira 1976) adapted in wheat rhizosphere elaborate few antibiotic including phenazine-1-carboxylic acid, 2,4 diacetylphloroglucinol (2,4-DAPG), pyoluteorin and pyrrolnitrin which are active against wide range of soil-borne pathogens (Kraus and Loper 1995).

A novel form of Fusarium wilt suppression was registered by Larkin et al. (1993a, b). In this system, development of a suppressive soil was achieved through the repeated cultivation of watermelon, but induction of the suppressive soil was limited to certain resistant cultivars. The development of suppressive soil was not associated with changes in populations of the pathogen *F. oxysporum* f. sp. *niveum* nor root colonization by *F. oxysporum*. Abundance of actinomycetes, fluorescent pseudomonads and total bacteria were higher in soil and the rhizosphere of watermelon in the suppressive soil. Further work with diverse groups of microorganisms isolated from these soils indicated that suppression was due predominantly to increases in specific populations of non-pathogenic *F. oxysporum* selectively enhanced in response to cultivation of particular watermelon cultivars (Larkin et al. 1996). The mechanism of action of some isolates representative to these fungal populations was shown to involve induced systemic resistance.

Harnessing the potentiality of soil suppressing microbial communities and their management through adaptive soil management is an important practical means to manage diseases in agro-ecosystem.

14.5 Microbial Integrity for Plant Fitness Under Acid Stressed Soil

Soil acidity is a global problem in crop production. About 40% cultivated land is greatly affected by soil acidity. Despite ample N, P, K supplementation in soil, crop productivity in acid soils is still below average. This is due to ionic toxicity, particularly Al toxicity which is a yield-limiting factor in acid soil (Marschner 1991). Availability of phosphorus is also restricted due to formation of relatively insoluble Al and Fe phosphate in acidic soil.

Acid soil is not at all problem soil. Rather it is the nature of soil as those of other soil types. Reclamation of acidic soil with the application lime stone is conventional mitigation option. But it is not a permanent solution. It recurres within year or two, thus, involves a recurring cost—unaffordable to poor farmers of universally inhabitant of acidic locality in the globe. Moreover, lime induced CO_2 production as a source of greenhouse gas is claimed by the environmentalists. Under this context, adaptive soil management that will help the crop plant to acclimatize in existing system without hampering the current environmental health. Encroaching deep soil by selecting deep rooted crop plants, root-induced changes in rhizosphere such as pH increase, release of chelator like amino acids, organic acids for aluminium and augmentation of autochthonous acidophilic beneficial microorganisms, particularly mycorrhizae for increased root surface are the possible adaptive management options for acid soil.

Fungi by acidophilic in nature can improve the plant fitness to an acid soil. Especially mycorrhizal association with crop plants in acidic soil evolves adaptive mechanisms to improve plant fitness in acidic soils having low plant available phosphorus (Marschner 1995; Dodd 2000). Plant-mycorrhizal symbiotic association enhances plant ability to exploit more soil nutrient, particularly, phosphorus and zinc by virtue of extended root surface due to fungal mycelial envelop on plant root (Dodd 2000; Marschner 1998). It is interesting to note that the length of mycorrhizal fungal thread in each centimeter of root may be in the range of 10–100 m in P-deficient soils (McGonigle and Miller 1999). Benefits derived from plant-fungal association are more conspicuous in soil generally poor in nutrients. 70–80% more phosphorus; 50 and 60% more Zn and Cu uptake were recorded in a pot experiment with mycorrhizal inoculated white clover (Li et al. 1991).

Mycorrhizal colonization of plants enhances their ability to explore the soil for P through the action of the fungal mycelium. This results in increased exploration of the soil for available nutrients and delivers more mineral nutrients, particularly P, to plant roots (Dodd 2000; Marschner 1998). It is estimated that the extent of fungal mycelium may be in the range of 10–100 m per cm root or per gram of soil under field conditions in P-poor soils (McGonigle and Miller 1999). In general, the contribution of mycorrhizal associations to the plant nutrient supply is larger in soils with poor availability of mineral nutrients than in soils rich in nutrients. In pot experiments, mycorrhizal colonization contributed to the total P uptake with between 70 and 80% and to the total Zn and Cu uptake with 50 and 60% in white clover (*Trifolium repens*) (Li et al. 1991). Mycorrhizal fungi also evolved adaptive mechanism to adjust acidic condition by maintaining narrow pH optima in their cells for carrying out essential enzymatic activities in acid soil (Leake and Read 1997). The colonization density of the ectomycorrhizal fungal species *Cenococcum geophilum* increased on beech (*Fagus sylvatica* L.) with increasing acidity (Kumpfer and Heyser 1986). In addition to mycorrhizal fungi, bacteria can improve plant fitness in acidic soil (Fierer and Jackson 2006) although their distribution itself is controlled primarily by the soil pH (Fierer and Jackson 2006). Acid smart autochthonous ectomycorrhizal fungi with site-adapted rhizosphere bacteria are helpful to the crop plants to be fit in acidic soil for their growth and productivity.

14.6 Microbial Integrity for Plant Fitness Under Saline Stressed Soil

Soil degradation through salinity is of universal concern. Soil salinity adversely affects plant performance through osmotic stress, ion toxicity and poor uptake of essential nutrients (Lauchi and Epstein 1990). High salinity results in poor soil physical and chemical attributes including unstable soil aggregates, impervious subsoil consequently low infiltration rate and hydraulic conductivity as well as surface encrustation which lead to erratic seedling emergence and poor crop stand (Choudhary et al. 2004; Sharma and Minhas 2005).

High salts content not only affect physical and chemical properties of soil but also affect microbiological properties of soil. Increases in salinity have been shown to decrease soil respiration rates and the soil microbial biomass (Pathak and Rao 1998). Less microbial abundance and its associated functions in saline soils are due to osmotic stress caused by higher concentration of different salts in soil solution (Oren 1991). Ionic toxicity resulted from higher concentration of chloride (Cl^-), sulphate (SO_4^{2-}), carbonate (CO_3^-), bicarbonate (HCO_3^-), sodium (Na^+) also inhibits microbial preponderance in elevated saline condition (Zaharan 1997).

The performance of β-glucosidase enzyme involved in C mineralization declined exponentially with increasing salinity (Rietz et al. 2001). Increased salinity induces reduction in soil microbial biomass which, in turn, decline in potential mineralization of easily transformable nitrogen in soil. A decrease in microbial biomass C and microbial activities with a rise in salinity is probably one of the reasons for poor crop growth in coastal saline soils (Tripathi et al. 2006).

The salinity induces reduction of fungi may reduce the decomposition of complex organic materials like lignin, cellulose, hemicelluloses, etc., in saline soils (Bardan 1994). Nitrogen transformation like mineralization, immobilization, nitrification and denitrification is poor in saline soils. Conditions which disturb the N cycle or that lead to the disappearance of nitrate from saline soil through the denitrification process might affect soil fertility and the existence of plants and microorganisms in these habitats. Elevated salinity induces the shifting of microbial communities to relatively smaller stressed communities with inferior metabolism (Yuan et al. 2007).

Numbers of management approach have been tried to impart salt tolerance in crop plants. These include classical breeding, selection of elite germplasm and crop improvement through genetical engineering. But their adaptability under varied salinity level in field condition is poor. A simple, farmers' user friendly and less expensive approach for plant production under salt stressed situation is adaptive soil management. These include rotation of perennials with annuals (phase farming), mixed planting (alley farming intercropping), site-specific planting (precision farming) (Munns 2002), etc. In spite of their efficiency to check yield loss under saline stress condition, implementation of these technologies in farmers' domain is limited due to higher cost involvement. In practice, development of low cost, easily adaptable and efficient approaches for salinity stress management is a challenging task to the researchers. However, specific microbes co-adapted in the rhizosphere of salt tolerant crop varieties have a silver line in this aspect.

PGPR by virtue of elaborating plant growth hormone indole-3-acetic acid (IAA) induce plant growth even under salt stressful environment by adjusting hormonal balance in plant system and trigger the initiation of lateral roots for better establishment in saline soil.

Exo-polysaccharide (ESP) producing microorganisms, on the other hand, bind cations, particularly, Na^+ and, thus, protect the plant from ionic toxicity of Na^+ under saline condition.

In this context, the role of cyanobacteria is of great importance. Cyanobacteria are salt feeding organisms adapted in saline soil and help the crop plants to remain fit even under high salt environment. Cyanobacteria in saline soil improve soil structure (Rogers and Burns 1994) and hydraulic conductivity (Malam et al. 2001) by virtue of its extracellular polysaccharides. Cyanobacteria also regulate the chemical properties of soil in favour of crop plants (Apte and Thomas 1997). As a phototrophic diazotrophs, they fix atmospheric nitrogen and also fix CO_2 to produce biomass in soil. Availability of P and S is also improved by cyanobacterial inoculation (Hashem 2001).

Rhizobacteria co-adapted in crop plant rhizosphere in saline soil influence the health of plant by adjusting ACC (a biologically active stress signaling molecule). ACC is a precursor of ethylene. Under salt stress situation, plant ethylene endogenously regulates root and shoot growth. Due to excessive ethylene in plants under

Table 14.1 Microbes and possible mechanisms for salt stress alleviation of different crops (Grover et al. 2011)

Salt tolerant microorganism	Test crop	Possible mechanism
Achromobacter piechaudii	Tomato	Synthesis of ACC-deaminase
Piriformospora indica	Barley	Increased antioxidative capacity
Arbuscular mycorrhizal (AM) fungi	Sorghum Corn Clover	Increased water circulation Improved osmoregulation and proline accumulation
B. amyloliquefaciens	Wheat	Restricted Na^+ uptake
Rhizobium and *Pseudomonas*	Wheat	Restricted Na^+ uptake

saline stress condition, root and shoot growth are hampered. Rhizobacteria elaborate ACC-deaminase enzyme which utilize ACC for nitrogen and energy. Thus, the deleterious effect of ethylene is reduced. Plants, thus, overcome salt stress and establish in saline soil (Glick et al 2007). Under saline condition ACC deaminase elaborating bacteria are co-evolved and thus, help in elongation of roots which secure the plant to uptake huge water from deep soil.

Direct mechanisms of plant growth promotion include those metabolisms that, by supplying nutrients to the plant, enhance its fitness. Halotolerant bacteria solubilize insoluble inorganic phosphate, fix atmospheric nitrogen and produce ammonia, thus contributed in plant nutrition. In addition to direct PRPR activities, several rhizobacteria elaborate protease enzyme. This property indicates their role as biocontrol agents (Table 14.1).

14.6.1 Adaptation of Bacteria to Saline Environments

14.6.1.1 Osmoregulation

Osmoregulation is the active regulation of the osmotic pressure of bacterial cell fluids to maintain the fluid balance and the concentration of the salt in solution to keep the fluids from becoming too diluted or too concentrated. In saline soil, bacteria adapt themselves to cope with extracellular ionic stress (Galinski and Trüper 1994). They do so by corresponding changes in the intracellular concentration of specific organic solutes (Csonka 1989). Soil microclimate influences the intracellular specific ion content which, in turn, affects the osmoregulation ability of halophilic bacteria. Bacteria of this nature acclimatize themselves by maintaining cell volume almost constant in wide range of extracellular salinity (Csonka and Hanson 1991). Therefore, bacterial cell membrane acts as primary barrier showing adaptive changes in the changing salinity in the environment (Thiemann and Imhoff 1991). For osmoadaptation, halophilic bacteria generally follow two distinct pathways—the KCl type and compatible solute type (Galinski and Trüper 1994). In the KCl type approach, the bacteria adjust the cytoplasmic KCl concentration with surrounding environment to attain an osmotic equilibrium. This type of osmoadaptation is associated with alteration of cell physiology which, in turn, protects metabolic and regulatory functions. The KCl type of osmoadaptation is commonly found in archaebacteria and also eubacteria. The compatible solute pathway, on the other hand, is basically adopted by eubacteria and few members of archaebacteria (Nicolaus et al. 1989). The compatible solutes are organic osmolytes like glycine betaine (N,N,N trimethyl glycine), proline, glutamine, N acetylated amino acids, N-derivatized carboxamines of glutamine, sugars and sugar polyol derivatives (Wohlfarth et al. 1990). In addition ectoines are also reported as compatible solutes (Talibart et al. 1994). These are responsible for making osmotic balance and compatible with cell metabolism. They are sometimes called osmoprotectants as they are salt antagonists or salt protecting agent.

Among the compatible solutes glycine betaine is reported to be most potential one for bacteria under condition of hyperosmolarity (Imhoff and Rodriguez-Valer 1984). Phototrophic species (Truper and Galinski 1990) and cyanobacteria (Imhoff 1986) are also reported to elaborate this solute to protect them from exogenous salinity.

Proline is an active osmolyte in the class of osmoprotectant for several bacteria. Gram positive bacteria elaborate proline upon exposure to osmotic stress (Koujima et al. 1978). Whereas gram negative bacteria accumulate proline from the surrounding environment and solely dependent on exogenous sources for osmotic balance (Le Rudulier and Bouillard 1983; Csonka 1989). Sugar like sucrose, trehalose also exhibit the properties of osmoprotectant in some microorganisms (Galinski and Trüper 1994).

Salt smart microbes by virtue of its adaptation and elaboration of biologically active substances in saline soil improve the plant fitness even though saline soils are physiologically dry soil.

14.6.1.2 Cell Morphology and Structural Change Under Saline Stress

On exposure to external salinity, bacteria overcome salt stress by modification of cell morphology in unique way. Gram negative *Azotobacter vinelandii* (Knowles and Smith 1971), *E. coli* (Baldwin et al. 1988), *Pseudomonas fluorescens* (Parente and Silva 1984) usually undergo cell elongation to withstand salt stress. The cell shape, size, arrangement as well as synthesis of building block biomolecules like proteins, lipopolysaccharides, more so, the genetical material of *Rhizobium*, for example, are modified in salt stressed environment (Zahran 1991, 1992a, b). These alterations influence the basic host-rhizobia symbiotic interaction. On the other hand, gram positive bacteria Bacillus, Staphylococcus adapt themselves in salt affected soil by thickening and enlarging their cell by several times. Endospore formation is common phenomenon in *Bacillus* to avoid salt hazard (Kudo and Horikoshi 1979; Weisser and Trüper 1985; Zahran et al. 1992). *Staphylococcus*, on the other hand, forms multiple chains and reduces its cell volume to be less affected from salt stress. On the whole, bacterial adaptation in hyperosmotic condition depends on the composition of bacterial cell wall, particularly, peptidoglycans—a rigid polymer consisting of sugars and amino acids that forms a mesh-like layer outside the plasma membrane of most bacteria, its stability and functioning (Koch 1984). Variation in protein, lipids and fatty acids composition of peptidoglycan

Table 14.2 Effects of PGPR strains on tomato (cv. Belle) shoot length and fruit yield in salt stress soil

Treatments	Plant height (cm)	%	Fruit yield (kg/m^2)	%
None	118.2 + 3.9	100	13.9 + 1.5	100
P. putida TSAU1	154.4 4.9[a]	130	16.4 1.6[a]	117
P. chlororaphis TSAU13	149.8 7.1[a]	126	15.6 1.2[a]	112
P. extremorientalis TSAU20	152.5 7.5[a]	128	17.0 1.2[a]	122

[a]Significantly different from the control at $P < 0.05$. Maheshwari et al. (2013)

layers in bacterial cell wall under salinity condition predicts the superiority of bacterial species to be adapted and performing necessary cell functioning (Thiemann and Imhoff 1991). Negatively charged lipids in cell wall are commonly found in bacteria adapted in elevated salinity (Russel and Adams 1991; Thiemann and Imhoff 1991). *Halomonas elongata*, for example, is able to live in a wide variety of salt concentrations (0.05–3.4 M) because it alters the cell physiology in ways which increase the structural integrity of walls and increase amounts of negatively charged lipids (Vreeland et al. 1984, 1991).

Saline soils are poor in plant available nitrogen content (Sprent and Sprent 1990). So, plant responses well to applied nitrogen (Valiela et al. 1976). One of the natural sources of nitrogen in saline habitat is diazotrophic N_2 fixation by free living N_2 fixing bacteria (Casselman et al. 1981; Whiting and Morris 1986). Diazotrophs are best fitted and co-adapted in crop plant rhizosphere in low O_2 tensioned saline soil and performed well by facilitating their nitrogenase enzyme system to be more functional. Nitrogen fixation and its availability have tremendous impact in saline habitat bacteria to synthesis compatible solutes like proline, glutamine and their derivatives. These amino acids are used as osmoprotectant for adaptation of bacteria in saline soil (Weisser and Trüper 1985; Imhoff 1986). Huge numbers of free living *Azotobacte*r (Wollenweber and Zechmeister-Boltenstern 1989) and phototrophic cyanobacteria well adapted under saline soil have been reported (Paerl et al. 1981).

Effectiveness of salt smart microorganisms for survival of crop plants and sustenance of yield under saline environment was also demonstrated in other experiment (Table 14.2).

Evolving efficient, low cost, easily adaptable methods for the abiotic stress management is a major challenge. Worldwide, extensive research is being carried out, to develop strategies to cope with abiotic stresses, through development of salt and drought tolerant varieties, salt smart microbial consortia, shifting the crop calendars, resource management practices, etc. (Venkateswarlu and Shanker 2009).

14.7 Microbial Integrity for Plant Fitness Under Moisture Stressed Soil

Food security for the projected 8 billion world population by 2030 is a challenge for agriculture sector. Shortage of irrigation water and upcoming drought are predicted to aggravate the agricultural activities further, more so, in newly expanded agriculture in low fertile areas to feed ever-growing population. So, it is widely urged to evolve suitable technology for successful crop production under restricted water availability.

Numbers of mitigation strategies have been tried to develop crop varieties with inherent capacity to withstand moisture stress. These include classical breeding, selection, marker assisted molecular breeding and genetical engineering (Fleury et al. 2010). Tolerance to moisture stress is expressed by conjoint response of multiple small genes. Intricacy of those genes responsible for moisture stress tolerance in crop plant is not fully understood (Price et al. 2002; Wang et al. 2003). Furthermore, multiple stressors in the environment affect crop plants simultaneously or sequentially; alone on in combination. Thus, selection moisture stress tolerant phenotypes are complicated (Niinemets 2010). In this context, simple, workable and low-cost technologies are deemed necessary for plant production under drought stressed situation. Adaptive soil management including conservation agriculture, mulching, rotation with deep rooted crops, water harvesting, etc., are simple technologies adopted by the farmers.

The capacity of PGPB to sustain crop growth under restricted moisture has frequently been claimed in agriculture system. This capacity is basically vested on gram positive rhizobacteria because of their endospore forming property that help in survivability through aggressive colonization under moisture stress condition (Timmusk 2003; Timmusk and Nevo 2011; Timmusk and Behers 2012a, b; Timmusk et al. 2013). As symbiotic plant growth-promoting bacteria (PGPB) has been recognized as broad-spectrum means to improve plant performance under moisture stress environment by different authors (Timmusk and Behers 2012a, b; Yang et al. 2009; Kim et al. 2013).

Drought is a stress to microbial communities. Some species cope with moisture stress through ecological adaptation, including cell modification and metabolic regulation or adapted to more favourable zone. In other way, species may adjust moisture stress through evolutionary path ways (Cavender-Bares and Bazzaz 2000; Winkel et al. 2001; Timmusk and Behers 2012a, b; Yang et al. 2009). Such evolution has been confirmed under the response to altered precipitation patterns (Kim et al. 2013; Timmusk and Wagner 1999; Mayak et al. 2004; Timmusk 2003). This adaptive plant response to moisture stress is important phenomenon in the rapidly changing environment for plant growth and performance.

Plant adaptation to moisture stress is facilitated by genetic changes in populations of closely associated microbial symbionts (e.g. fungal endophytes or mycorrhiza) (Rodriguez 2008; Rodriguez and Redman 2008). Adaptation of plant to moisture stress is facilitated more by belowground co-evolved microbial guild than by the evolutionary adaptation of plant traits. Belowground microbial communities quickly response to moisture stress and act accordingly to protect the crop plant and make them fit to survive in stressful environment. In an experiment, plant fitness in terms of flower and fruit production under moisture stress increased when plants are inoculated with moisture tolerant microbes. Plant inoculated with wet-adapted microbes produced decreased fruit production. While, lesser decline in fruit production was noticed in dry-adapted microbial inoculated plants (Fig. 14.1).

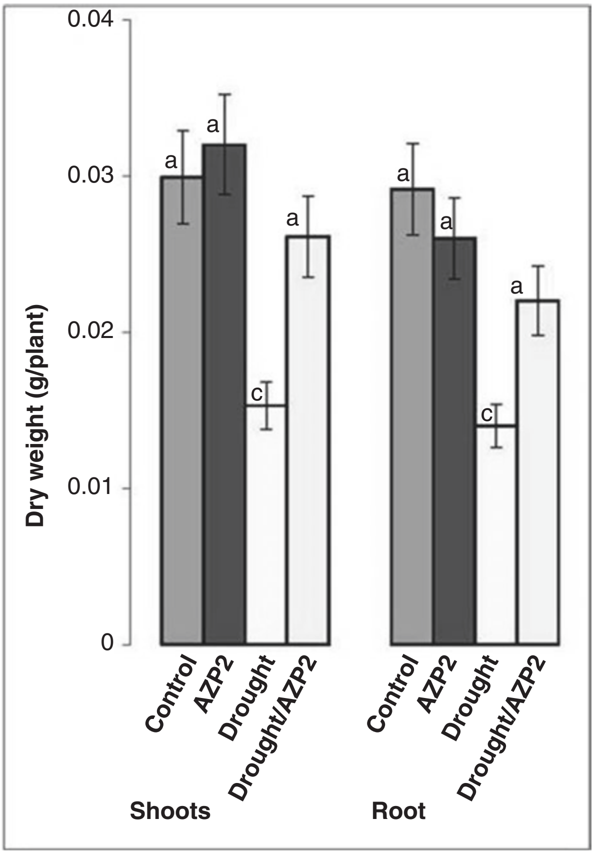

Fig. 14.1 Enhancement of wheat (*Triticum aestivum*) drought tolerance by *Bacillus thuringiensis* AZP2 in sand soil (Timmusk et al. 2014)

Figure shows the effect of drought tolerant microbial inoculation (AZP2) on dry matter yield of wheat plant after 8 days growth without watering. Treatments labeled with same letter are not statistically significant.

Microbial communities evolved under prolonged moisture stress are highly resistant to changing moisture regimes. They affect plant fitness to moisture stress in two pathways. First, resistant microbes under moisture stress facilitate nutrient transformation to make nutrient, particularly, nitrogen availability to the plant for their survival in the challenging environment.

But N availability can be compensated by nitrogen fixing bacteria adapted in rhizosphere of crop plants in moisture stressed soil. Second, moisture stress situation reorganizes the relative abundance of mutualists, antagonists and pathogens. Plant derives fitness benefit from beneficial interaction in plant–soil–microbes continuum (Yang et al. 2009).

Table 14.3 Microbes and possible mechanisms for drought stress alleviation of different crops (Grover et al. 2011)

Microorganism	Crop	Mechanism
Pantoea agglomerans	Wheat	Production of EPS which affects the structure of rhizospheric soil
Rhizobium sp.	Sunflower	Production of EPS which affects the structure of rhizospheric soil
Azospirillum sp.	Wheat	Increased water circulation
Chromobacter piechaudii ARV8	Tomato pepper	Synthesis of ACC-deaminase
Variovorax paradoxus	Pea	Synthesis of ACC-deaminase
Arbuscular mycorrhiza (AM) fungi	Sorghum	Increased water circulation
Pseudomonas mendocina and *Glomus intraradices*	Lettuce	Increased antioxidative status
Bacillus megaterium and *Glomus* sp.	Clover	Production of indole acetic acid and proline
Pseudomonas sp.	Pea	Decreased ethylene production
Pseudomonas putida-P45	Sunflower	Production of EPS which affects the structure of rhizospheric soil

Enhancement of moisture stress tolerance in plant by co-adapted rhizobacteria is attributed primarily by: (1) elaboration of phytohormone like compounds, (2) production of ACC (1-

aminocyclopropane—1-carboxylate) deaminase enzyme to degrade ACC for reducing ethylene concentration to encourage root elongation and ramification under water stress condition, (3) developing induced systemic resistance in plant, and (4) formation of microbial film, i.e. extracellular matrix embedded with diversified microbes (Timmusk and Nevo 2011). Biofilm provides sugar, polysaccharides which, in turn, improve soil structure by binding soil particles and consequently increased water holding capacity in root zone of crop plants. Hydrated microenvironment resulting from polysaccharides rich soil improves plant fitness in limiting moisture condition (Chang et al. 2007).

Microbial polysaccharides can bind soil particles to form microaggregates and macroaggregates. Plant roots and fungal hyphae fit in the pores between microaggregates and thus stabilize macroaggregates. EPS producing bacteria co-adapted with plant exhibit higher resistance to moist stress as a result of improved soil structure (Sandhya et al. 2009) (Table 14.3).

Root architecture is an important trait of crop plants to be adapted in moisture stress condition. Inhibition of lateral root growth and enhancement of vertical root growth are adaptive response, because under moisture stress condition water availability is higher in subsoil layers. This response is more under prolonged moisture stress. Furthermore, denser and deeper root formation facilitated by moisture stress tolerant microbes encourages the rhizobacteria to form biofilm surrounding root surface. The mucilaginous matrix of biofilm accumulates biologically active substances elaborated by microbes in the root surface to be easily up taken by plant

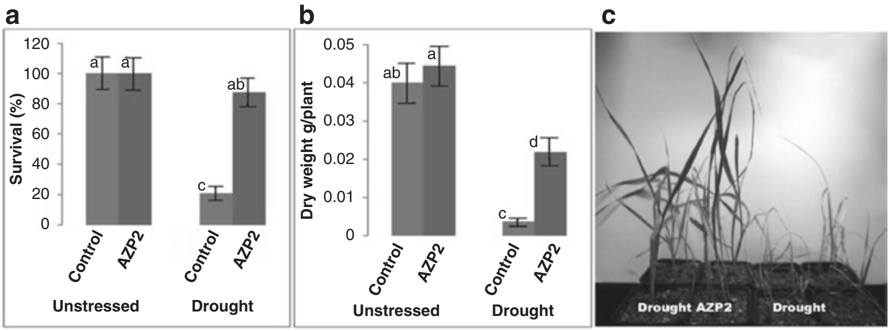

Fig. 14.2 Increase of wheat drought stress tolerance by *Bacillus thuringiensis* AZP2 in sand mixed with 10% greenhouse soil (Timmusk et al. 2014)

root. Thus, plant survivability and performance are secured under moisture stress condition. Wheat root inoculation with drought tolerant bacteria AZP2 improved survival rate of wheat seedling (a) growth in terms of dry matter yield, (b) physical appearance of wheat crop after 14 days of drought, and (c) suggests the role of drought tolerant bacteria (AZP2) on the survivability of crop under severe drought condition.

Presence of alginate, a bacterial polysaccharide, improves water retention and slow releasing capacity of biofilm (Halverson 2009; Hay et al. 2013; Donati and Paoletti 2009) and, thus, makes root zone hydrated during the plant growing period. Thereby, alginate improves moisture stress tolerance to crop plants (Fig. 14.2).

Co-adaptation of such water-smart microbes with drought tolerant crop rhizosphere and the water economy extended by them will be the future line of research to formulate microbial consortia and their commercial use in arid and semiarid region.

Reactive oxygen species (ROS) are highly reactive ions and free radicals involving O_2 molecules, cause tissue injury. They are the indicator of drought stress in crop plant. Drought tolerant rhizobacteria are capable of synthesizing ROS scavenging enzyme, especially under drought stress and increase photosynthetic efficiency and thus, helping the plants to cope with drought stress. Similar alterations in antioxidative capacity by stress-alleviating microorganisms have been reported earlier (Wang et al. 2012; Mastouri et al. 2012). ROS detoxification enzyme is an important microbial trait for screening drought stress alleviating potential microorganisms. Superoxide (O_2^-) and hydrogen peroxide (H_2O_2) are other two species of antioxidants found in plant under drought stress. Rhizobacteria by virtue of elaborating superoxide dismutase (SOD) (EC 1.15.1.1) and catalase (CAT) (EC 1.11.1.6) scavenge those antioxidants and help the plant to survive in restricted moisture condition (Mastouri et al. 2012).

Tailoring existing cropping systems with the inclusion of deep rooted cultivars inoculated with PGPR and moisture stress tolerant biofilm producing rhizobacteria may be adaptive water management strategy in future.

14.8 Conclusion

Agriculture is facing multiple stresses like compaction, intensification, salinity, acidity, drought and invasion by weeds and pathogens. In future, agriculture will experience such stresses in more intensive way due to rapid climate change and anthropogenic activities. It is inevitable. Mitigation options are designed to overcome the effect of stresses on crop production. But progress in this line of activities is slow and achievement is noticeably poor due to technological constraints, excessive time taking and necessarily high cost involvement. Resource poor farmers of developing countries are vulnerable to such stresses, particularly farmers of developing countries consistently need ready to use technology adapted to the existing situation not against the nature. Potential adaptive soil management strategies are identified and popularized. But necessary attention did not paid on co-adapted plant growth promoting rhizobacteria which work silently amidst stressful environment and stimulate plant fitness to produce expected yield. Securing expected yield under the paucity of irrigation water is a challenging issue in future agriculture. Water-smart microorganisms by virtue of its goodness could provide suitable breakthrough in the field of water management.

Data are also available regarding microbes mediated alleviation of salinity, acidity, compaction intensification and invasion. Most of the data are generated from laboratory condition or greenhouse experiments. Well-designed field experiments are to be conducted to understand the relationship between yield loss and level of stress imposed. But, conducting such experiment in field condition is very difficult because of unable to maintaining variability of stress levels under open field condition. However, using available technology, more precise research programmes are to be conducted in this field.

Adaptive management is knowledge-based. So, to explore and exploit the goodness of co-adapted soil microorganisms, understanding the unique microbial properties, strong observation, constant monitoring, knowledge acquiring, fine tuning and its shearing by the stakeholders in participatory mode is deemed necessary. This will ultimately help to develop designer microbial inoculants to cope the crop plants of the upcoming environmental stresses for assured productivity under stressful condition.

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Impact of Agricultural Management Practices on Mycorrhizal Functioning and Soil Microbiological Parameters Under Soybean-Based Cropping Systems

15

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Abstract

The use of modern agricultural techniques for enhanced production has been advocated, however, its impact on below ground microbial networks is overlooked and adversely affected. The abiotic stresses like temperature (heat, cold chilling/frost), water (drought, flooding/hypoxia), radiation (UV, ionizing radiation), chemicals (mineral deficiency/excess, pollutants heavy metals/pesticides, gaseous toxins), mechanical (wind, soil movement, submergence) are responsible for over 50% reduction in agricultural production. On the other hand, organic farming practices yield fruitful results. This has highlighted the emerging need of switching over to some eco-friendly agricultural practices which can enhance the growth of plant, improve soil quality, mitigate drought without having adverse impacts on environment. Rhizosphere which is the narrow zone surrounding the roots of plant (Hiltner 1904) contains microbial communities which

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have the potential to benefit plants. Arbuscular mycorrhizal fungi are obligate symbionts which form association with about 90% of the land plant species (Gadkar et al. 2001). However, agricultural practices like tillage, crop rotation, fallowing, organic farming, fertilizers, etc., influence the functioning of AMF in many ways. Soybean is rich in phytochemicals that are beneficial for human beings. The inoculation of soybean and some other crops including cereals, pulses, and other leguminous crops with AMF leads to an enhancement in abiotic stress tolerance, disease resistance, overall growth, soil carbon sequestration, nutrient uptake, etc. This chapter summarizes the overall impact of different agricultural practices on mycorrhiza and other soil microbial communities under soybean-based cropping system.

Keywords

Agricultural practices • Arbuscular mycorrhizal fungi • Soybean • Soil microbial communities

15.1 Introduction

The green revolution includes the use of artificial fertilizers, pesticides, and high yielding crop varieties which resulted into increased in production of crops like wheat, corn, soybean, and rice. However, this has increased concerns over environmental pollution posed due to the uses of weedicides, pesticides, chemical fertilizers, and other intensive chemical inputs. This has caused toxic effects to the environment, disturbing soil structure and soil quality, i.e., affecting the biological processes. The harmful effects of fertilizers and pesticides can be seen in the form of deterioration of water quality and adverse effects on human health and animal life despite of getting higher crop production (Dubrovsky et al. 2010; Rohr and McCoy 2010). A paradigm shift towards organic farming and inoculating the soils with beneficial soil microbes like mycorrhiza and other plant growth promoting microbes will help in combating this problem and improve soil quality. Turner (2004) proposed that better use of rainfall and increase in the yield of dryland crops can be achieved through practicing minimum tillage which may help in controlling the insects, weeds, diseases and maintain soil fertility. Conservation tillage was defined by Hobbs et al. (2008) as a system that involves the amalgamation of least soil disturbance in the form of no tillage along with mulch and rotations that fit the future scenario of sustainable cultivations. The combination of cover crops, crop residue mulch can restore lost soil organic pool (Lal 2004) and maintained mycorrhizal biomass in the soil. Conservation tillage leads to carbon sequestration by increasing soil aggregation in terms of microaggregates and soil organic carbon (SOC) storage beneath deep soil layers (Lal and Kimble 1997).

Soybean is an important oilseed crop of the world being frequently grown with non-legumes and cereals in the form of intercropping or rotation. Yield advantages have been obtained in case of intercropping systems like maize/soybean (Ghaffarzadeh et al. 1994) and wheat/maize-wheat/soybean (Li et al. 2001). AMF are obligate biotrophs from the phylum Glomeromycota (Schubler and Walker 2010), whose relationship formed with the roots of more than 90% of the terrestrial plant families of higher plants and benefits the plants in the form better nutrition and growth and help in drought resistance (Smith and Read 1997; Augé Robert 2001). Plant species like some members of Brassicaceae do not support mycorrhizal growth (Wang and Qiu 2006), therefore it becomes significantly important to include mycorrhizal crops in rotation. The inclusion of mycorrhizal hosts like soybean in the rotation with crops like maize favor AM fungal (AMF) population in the soil (Higo et al. 2010; Sharma et al. 2012). By means of mycorrhizal associations direct N-transfer from between legumes and non-legumes takes place (Szumigalski and Van Acker 2006). AMF gets photosynthate from plant in cortical cells of plants as well as in surrounding rhizosphere (Smith and Read 1997) and beyond the surface of the root through the extension of hyphae of AMF (Jakobsen et al. 1992).

Soil disturbance in the form of tillage can break AMF hyphae and render it non-infective, i.e., unable to colonize a living plant root (Jasper et al. 1989). Apart from the benefits mentioned above AMF also produces a glycoprotein called glomalin which improves soil aggregation and soil carbon sequestration (Wright and Upadhyay 1996). It plays an important role in heavy metal sequestration and storage of carbon (Cornejo et al. 2008).

In this chapter emphasis has been given upon how different agricultural management practices influence mycorrhizal population in soil under soybean-based cropping system. AMF glycoprotein glomalin a crucial soil health indicator said to be influenced by several factors like wildfire (Gispert et al. 2013), tillage (Avio et al. 2013), and crop rotation (González-Chávez et al. 2010). Apart from the impacts of crop and soil management practices influencing AMF, we have also discussed glomalin which can be used as an important marker to study the impact of various soils, nutrient, and weed management practices on soil.

15.2 Impact of Agricultural Crop and Soil Management Practices on AMF or AM-Associated Parameters

Soybean (*Glycine max* L. Merrill) is an important mycorrhizal crop and is frequently grown in rotation with other crops. The dominance of a particular plant species (monocropping) might increase particular production of root exudates which resulted into adverse impacts on AM population and overall crop yields which can be overcome by rotating crops by introducing other crops in the cycle, i.e., crop rotation (Johnson et al. 1992). According to Scheublin et al. (2004) some mycorrhizal species might be chosen by a particular crop for colonization as observed in case of a few legumes. In some cases selection of host compatible AMF species might also occur (Mathimaran et al. 2007). Depending on the climatic conditions phosphorus addition to the previous crop or present crop (like flax) may reduce AM colonization (Monreal et al. 2011). Distinct AMF communities have been found to be present in organic and conventional farming where conventional farming was detrimental to a few native AMF species which were earlier maintained under organic farming (Oehl et al. 2004). According to Davis et al. (2012) among a

Table 15.1 Effect of crop and soil management practices on AM population changes/species compositions in soybean-based cropping systems

Crop and soil management practice	AMF population change/species composition	Reference
Crop rotation system with continuous corn-continuous soybean-fallow	Corn > Soybean > Fallow Corn— *Glomus albidum and Glomus etunicatum* Soybean—*Glomus constrictum*	Troeh and Loynachan (2003)
Corn monoculture, corn-soybean rotation	Higher AMF diversity in corn monoculture quantified in the form of AMF Biomarker: 16:1w5c	Zhang et al. (2014)
Ridge tillage (RT); no tillage (NT)	Higher AMF diversity in no tillage	
Conventional (CT) and no tillage (NT) with wheat-oat rotation	Higher AMF propagules under no tillage. Higher population of *Acaulospora* spp and *Scutellospora* spp was observed in wheat (CT) and oats (NT), respectively	Castillo et al. (2006)
Conventional tillage, chisel treatment, no tillage	Long term reduced tillage practice inhabits mostly non-*Glomus* species; conventionally tilled soils dominates in *Glomus* spp.	Jansa et al. (2002)
Tillage and N fertilization in maize	AMF composition influenced more due to N fertilization than tillage	Borriello et al. (2012)
Sole alfa-alfa with long term phosphorus fertilization	No significant effect either on AMF biomass or ribotype assemblage as determined by AMF Biomarker: 16:1w5c	Beauregard et al. (2010)
Fertilizer treatment on maize, soybean, and viola	P-fertilized maize plants reduced AMF colonization whereas soybean and viola plants did not	Gosling et al. (2013)
Organic and conventional farming, crop rotation with potatoes, winter wheat, beetroots, and grass-clover meadow	Higher AM population and diversity observed in organic farming; organic system dominates in *Acaulospora* and *Scutellospora*	Oehl et al. (2004)

conventionally managed two years rotation (maize-soybean) and two more diversified systems having 3 years (maize-soybean-small grain + red clover) and 4 years (maize-soybean-small grain + alfalfa-alfalfa) having a combination of organic manure and lower inorganic input, the benefits of diverse system in terms of production were always equal to or better than conventional system, despite of less intensified agricultural system. Studies on the influence of different soil and crop management practices on AM functioning and species compositions carried out by several workers (Table 15.1). Other facts about AMF which have been observed for different soils include the detrimental effects of P fertilization on AMF, increase in AMF species richness following the use of diverse crops and reduction in AM population due to tillage (Jansa et al. 2006).

15.2.1 Tillage Practices

To the microbial biomass in agricultural soils the sole share of AMF is largest (Olsson et al. 1997). Tillage disrupts hyphal network of AMF (Jasper et al. 1989). Tillage systems adversely affect AMF spore abundance (Galvez et al. 2001). In case of no tillage, the hyphae form the preceding crop serves as inoculum and remains intact in soil to colonize next crop (Brito et al. 2012) and could remain a source of inoculum for years (Smith and Read 1997). The mechanism for lower AM population in tilled soil was discussed by Borie et al. (2006) according to which, soil mixing as a consequence of tillage brings AMF propagules to the top soil surface thus reducing their efficiency to serve as inoculum to the succeeding crop in a crop rotation system. Taking mycorrhizal abundance as crucial signals for evaluating the tillage induced effects on AMF; Castillo et al. (2006) found higher spore density and percent root colonization under no tillage system. Under reduced tillage conditions AMF have been found to have faster root colonization and higher infectivity potential (McGonigle and Miller 1996).

AMF species might differ in their ability to grow in tilled soils. Jansa et al. (2003) found increased incidence of some *Glomus* species in disturbed soils where tillage hindered the growth of *scutellospora.* Whereas Castillo et al. (2006) found higher *Acaulospora* spore density in wheat managed with conventional tillage. Douds et al. (1995) found variation in *Glomus* species where *Glomus etunicatum* occurred with higher frequency in tilled soil and *Glomus occultum* spores were higher in no tillage soils. In the experiments of Avio et al. (2013) *Funneliformis mosseae* was abundant in tilled soils whereas *Glomus viscosum* and *Glomus intraradices* dominated in undisturbed soil. Tillage systems such as reduced tillage and no tillage coupled with herbicides have been adapted in various parts of the world so as to have an overall positive impact on soil structure, crop production soil water storage potential, and reduction of soil erosion as well as in energy and reduced mechanical efforts (Triplett and Dick 2008). No tillage supports AMF growth as Borie et al. (2006) observed highest AMF spore abundance and metabolically active hyphae in no tillage and found no tillage and reduced tillage equally efficient in maintaining higher glomalin and other soil chemical parameters like carbon, sulfur, and mineral nutrients. Agricultural management practices, cropping sequence, and previous crop are found to have stronger influence on mycorrhizal root colonization where the effect of tillage can be even higher than crops (Brito et al. 2012). Expressing the need of non-mycorrhizal root infection to be explored while evaluating mycorrhizal colonization, Mozafar et al. (2000) found higher AM colonization in roots of maize under no tillage than conventional tillage and chisel plow, but no such difference was observed in wheat which had higher incidence of non-mycorrhizal colonization than mycorrhizal one under above-mentioned tillage systems. No tillage benefits were observed by Mbuthia et al. (2015) in terms of productivity, enhanced total organic carbon, activities of enzymes related to C, N, and P, and copiousness of microbial communities. Avio et al. (2013) found higher total and easily extractable glomalin fractions in no tillage where no significant effect of nitrogen fertilization was observed on either fraction.

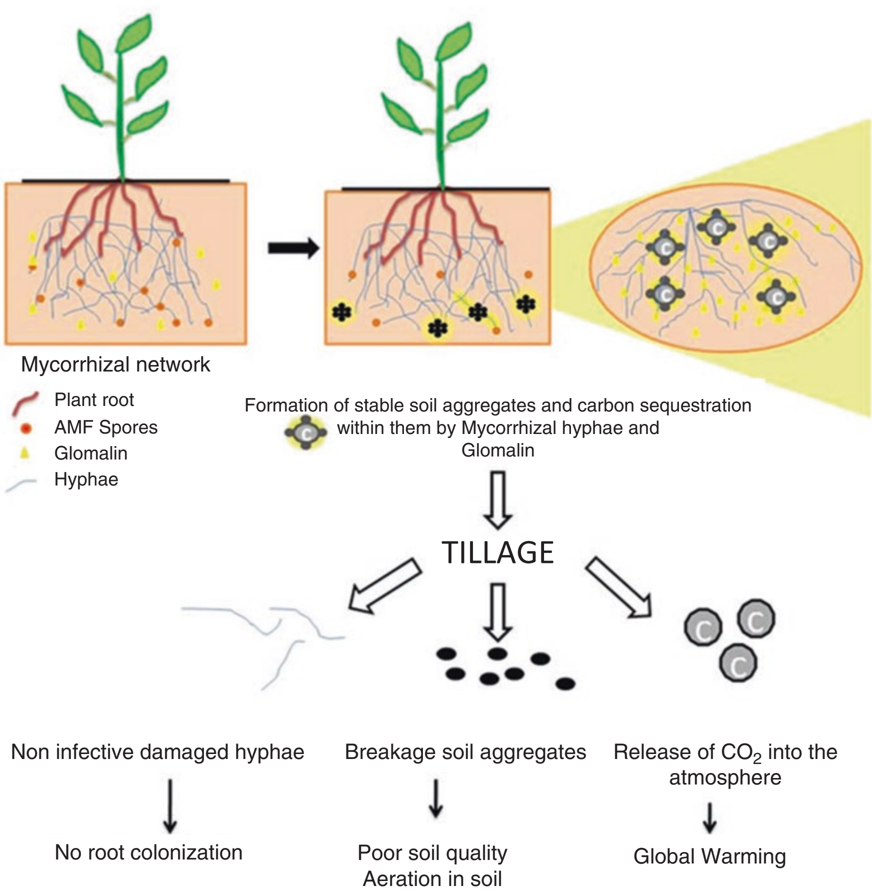

Fig. 15.1 Effect of tillage on AMF network structure, soil aggregates, and CO_2 sequestration

In the experiments of Lavado et al. (2001) among soybean, wheat, and corn, soybean appeared to be the most sensitive to tillage. However, adverse effects on nodulation and soil nitrogen were observed when high amount of maize residues were present on no till soil having soybean (Vanhie 2014) (Fig. 15.1).

15.2.2 Crop Rotation and Crop Sequences

According to Ngosong et al. (2012) a larger impact is created by crop rotation on soil microbes than organic/inorganic fertilizer treatments. The prevalence of *Gigaspora* in continuous soybean plots and *Glomus* in maize, milo, and fescue (grown in rotation with soybean) was observed by Hendrix et al. (1995). However, later growing soybean on plots dominant in *Gigaspora* decreased the unevenness between AMF communities on rotated and continuous plots. A rotation involving a non-mycorrhizal crop such as canola could decrease AM colonization in the succeeding crop, i.e., like maize, where no such effect was seen in case of soybean. The effect of canola could not be ameliorated by cover cropping with winter wheat which supports AM growth. However, no such effect was seen in second year of maize (Koide and Peoples 2012). In the experiment of Sharma et al. (2012) showed highest mycorrhizal spore density and infectivity potential in Soybean – Wheat – Maize – Wheat rotation and highest mycorrhizal colonization in Soybean + Maize – Wheat in the conventional reduced tillage system. These cropping systems also showed highest soil dehydrogenase and fluorescein diacetate hydrolytic activities in the reduced tillage system.

Fallow rotation induced risks include soil erosion which is not apparent in case of grasses and legumes (Michalson 1999). Soybean grown in rotation with wheat maintains abundance of AMF phylotypes and species richness at molecular level with 1.3 to 2.6 times greater stocked biomass of AMF assessed by its biomarker C16:1cis11 (Higo et al. 2013). AMF abundance and root colonization were found to be higher in soybean-sweet potato than fallow-mustard (Usuki and Yamamoto 2003). The adverse effects of soil purturbations such fallow and non-host crops tend to affect AMF size and vigor which makes hyphae prone to further damage and affect plant development irrespective of disturbances (Kabir et al. 1999). On contrary to above, the continuous cropping systems showed better results than rotated sequences as Tian (2013) found that AMF induced P uptake evident from activities of Acid phosphatase and Poly P was found to be higher in continuous maize as compared to maize-soybean rotation and ACP and Poly P showed positive correlation to arbuscules and C18:1cis11, respectively.

15.2.3 Fertilizers, Pesticides, Fungicides

AMF perform better in less fertile soil than the soils high fertility (Martinez and Johnson 2010). In case of maize rotated with leguminous and non-leguminous fallow, low phosphorus doses improve preliminary arbuscular and hyphal colonization with beneficial impacts on yield and nutrient uptake in terms of P and N (Muchane et al. 2010). Benefits of low P doses in terms better soil quality can be achieved via glomalin related soil protein, aggregate stability, phosphatase, and dehydrogenase activity as well as AM colonization and community structure (Alguacil et al. 2010). There is an important role of soil pH in shaping AMF community composition (Hazard et al. 2013) as soil pH below 5 in not favorable for *Glomus mosseae* (Wang et al. 1993). Liu et al. (2014) observed a decline in soil pH as a consequence of nitrogen fertilization which had negative influence on communities of AMF.

Impact of balanced fertilization with manure and straw amendment on C-sequestration, Bradford reactive soil protein (Glomalin) content, AMF spore abundance, and richness were also discussed by Wu et al. (2010). Combined application of NPK fertilizers with FYM has increased soil organic carbon than NPK alone and in terms of above ground biomass, soybean's share to carbon input on annual basis was found to be 29% where wheat contributed 24% (Vedprakash et al.

2007; Kundu et al. 2007). Diverse AMF communities were maintained in case of orchards managed with organic farming as compared to conventional counterparts (van Geel et al. 2015). N fertilization has a stronger impact on AMF assemblage as compared to tillage (Borriello et al. 2012) as N-fertilization exerts negative effects on AMF abundance and operative structures (Santos et al. 2006). Phosphorus fertilization is responsible for a significant decrement in AMF abundance (Chen et al. 2014). Considerably large reduction in mycorrhizal colonization has been reported in soybean due to phosphorus fertilization (Hicks and Loynachan 1987). However, in an alfa-alfa field with variable phosphorus doses for 8 years, no significant effect on AMF was observed as studied through AMF biomarker 16:1w5.

Fungicides, herbicides, weedicides, nematicides applied on crops to achieve an effective biocontrol could affect AMF population in soil. AMF are known to exhibit antagonistic effect against nematodes either by showing competitive effects or increasing host resistance to nematodes (Schouteden et al. 2015). However, the use of nematicides could affect AMF population in soil. Bakhtiar et al. (2001) did not find any increase in nematode number in uninoculated plants, whereas in case of mycorrhiza inoculated plants, spores of a particular species could be prone to nematode induced damage. The restoration of mycorrhizal colonization and spore densities adversely affected by nematode (Aphelenchus avenae Bastin) was achieved by recommended dose of nematicide fenamiphos (Bakhtiar et al. 2001).

In case of fungicides Benomyl treatment decreases AM colonization, where no significant effects were observed on other fungal populations (O'Connor et al. 2002). On the developmental stages of *Glomus irregulare*, i.e., spore germination, hyphal development to spore formation, Calonne et al. (2011) observed the harmful effects of fungicide propiconazole. Fungicide carbendazim has also been found to delay or even stop the symbiotic association between root and AMF (Dodd and Jeffries 1989). Fungicide chlorothalonil reduces root colonization by *G. mosseae* in soybean plants weather the doses are lower or higher (Venedikian et al. 1999). However, there are evidences of low or no effect of fungicides on AMF biomass. Fungicide azoxystrobin and pencycuron directed against *Rhizoctonia solani* were not detrimental to *Rhizophagus irregularis* when applied at threshold level. However, in the same study effect of flutolanil on intramatrical phase were observed (Buysens et al. 2015). Application of fungicide metalaxyl mycorrhizal colonization either increased or remained unaffected in maize and soybean roots in the experiments of Groth and Martinson (1983). Murillo-Williams and Pedersen (2008) also found any significant reduction in AMF root infection when fungicides were applied through seed application in soybean plants.

Herbicide glyphosate also exerts detrimental effects on AMF adversely affecting biomass in terms of hyphe and spores as determined through signature fatty acid 16:1w5 (Zaller et al. 2014).

A combination of three AMF species in the inoculum was found to be more susceptible to the damage caused by fungicides as compared to individual inoculation which also exerted beneficial effects on soil quality and host plant (Schreiner and Bethlenfalvay 1997). Jin et al. (2013) studied the effect of systemic and contact fungicides on AMF where AM colonization and host plant growth were hindered by former and only slightly affected by latter.

15.2.4 Soil Aggregation

Fine roots and AMF together lead to the formation of water stable aggregates (Miller and Jastrow 1992). Hyphal growth in the form of hyphal length and density has been found to be strongly connected to aggregate stability in terms of mean weight diameter of aggregates (Bedini et al. 2010). Variation may exist between AM fungal species in their ability to improve aggregate stability as *Glomus mosseae* was found to be more efficient in terms of improving aggregate stability of 2 mm size aggregates when compared to *Glomus etunicatum* and *Gigaspora rosea* (Schreiner et al. 1997). Similarly in the experiments of Miller and Jastrow (1992) a correlation was found to exist between % water stable aggregates and spore abundance of *Gigaspora rosea* whereas in case of *Glomus etunicatum* no such correlation was found to exist. Piotrowski et al. (2004) hypothesized that the combination of grasses and family Gigasporaceae produce greater hyphal length and biomass (Hart and Reader 2002) would promote aggregate stability, but they found lowest aggregate stability in the form of water stable aggregates and neither root biomass of grasses nor hyphal length of Gigasporaceae were found to correlate positively with aggregate stability in the form of WSA. In 1996, Wright and Upadhyay discovered glomalin which is a glycoprotein existing in two pools in soil, i.e., easily extractable (EEG) and total glomalin (TG) produced by AMF possessing role in enhancing aggregate stability. Due to complexities faced in its extraction (Rosier et al. 2006) involving co-extraction of polyphenols (Whiffen 2007) glomalin has been more precisely called as glomalin related soil protein, i.e., GRSP or Bradford reactive soil protein, i.e., BRSP (Rillig, 2004). Glomalin greater residence time in soil coupled with its positive correlation with water stable aggregates gives rise to long term soil aggregate stability (Rillig 2004).

The carbon held inside aggregates is respired to CO_2 as it becomes available to aerobic microbes when cultivation breaks the aggregates apart (Robertson and Grandy 2006). Better soil health could be achieved by adaption of tillage practices involving less disruption as in the studies of Karlen et al. (2013) the effect of such practices was indicated by lower scores of 'soil management assessment framework' of organic carbon, microbial indicators like microbial biomass carbon and potentially mineralizable nitrogen and some other soil quality parameters. Highest mycorrhizal propagules in terms of spores, total and active hyphae as well as both the fractions of glomalin were observed in a system following no tillage for 6 years where a correlation of GRSP with total hyphae and aggregate stability suggested the contribution of mycorrhiza to aggregates stability (Curaqueo et al. 2011). Zhang et al. (2012) found higher AMF and GRSP abundance in macroaggregates under no and reduced tillage system where a better soil moisture status in such systems also resulted in higher fungal and bacterial activities which lead to higher SOC and MBC in these aggregates. Zhang et al. (2014) also found that among ridge and no tillage system having sole maize with 2 years of maize-soybean rotation, under no tillage there were enhanced soil enzyme activities and microbial lipid content as quantified through PLFA.

15.2.5 Impact of Genetically Modified Plants

A better agricultural system with positive implications on environment will arise from new cultivars with better nutrient use efficiency grown with best management practices (BMPs) (Baligar et al. 2001). Glyphosate resistant soybean (GR or Roundup Reddy, RR) is one of the most cultivated transgenic crops globally. Nakatani et al. (2014) found that microbial biomass C, N and acid phosphatase and beta glucosidase activity remained unaffected by RR-transgene, herbicide, and weed management practice whereas growing area, cultivar, and cropping season had a greater role in it. Although transgenic soybean (glyphosate resistant) results in increased production and a decrease in the use of agrochemicals, there are some unanswered questions on their potential environmental impacts (Cerdeira et al. 2007). The lack of clear distinctions in AM colonization between GM and their conventional counterparts raises many questions on the impact of Bt crops on mycorrhizal symbiosis. The impact of such crops, release of such organisms into atmosphere, and effect on non-target microbes remain hidden (Giovannetti et al. 2005). In the field experiments of Cheeke et al. (2014), in terms of mycorrhizal growth parameters like AM colonization, spore diversity, Bt maize, and non-Bt maize weren't distinct from each other. A reduced level of AM colonization in Bt maize showed dependence on spore density of inoculum and fertilizer dose, where a comparatively higher spore density coupled with lower fertilizer dose had lower colonization (Cheeke et al. 2011). In transgenic pea plants modified for fungal pathogen resistance via gene insertion, the genetic modification (i.e., insertion of antifungal genes) did not affect mycorrhization as observed in the form of frequency and intensity of AM colonization as well as arbuscules in AM colonized and complete root section (Hassan et al. 2012).

In some cases genetic modification might not be responsible for occurrence of different effects in GM and non-GM plants. Powell et al. (2007) investigated genetically modified and conventional soybeans for colonization by *Bradyrhizobium japonicum* and AMF and found that these crops differed in level of mycorrhizal colonization and nodulation and the GM status of the plant was not the reason behind this. Knox et al. (2008) compared genetically modified cotton cultivars having insect resistance and glyphosate resistance with the conventional ones and found no difference in the level of mycorrhizal colonization where 70–80% colonization was attained in both the cases and no differences were observed in the growth and yield of either crop. Cheeke et al. (2014) found identical mycorrhizal colonization in Bt and non-Bt maize plots irrespective of the cropping history, i.e., whether the preceding crops were Bt or non-Bt, although spore abundance was higher in plots where previous crops were conventional. In case of native mycorrhizal fungi, de Vaufleury et al. (2007) did not find significant difference in the AMF colonization between GM and conventional maize and the MI_{50} (least dry weight of soil needed to colonize half of the plant) between the crops was also found to be identical, thus confirming the mycorrhizal nature of both the crops. On the contrary according to Liu (2010) during the cultivation of Bt transgenic plants, the fundamental expression of Bt insecticidal proteins might impair a few crucial steps of mycorrhizal symbiosis establishment and this expression concurs with mycorrhizal life cycle round the year resulting in adverse effects on AMF species richness later on. This was indeed supported by the studies of Cheeke et al. (2012) who found lower AMF colonization in Bt maize than non-Bt parental lines and the expression of particular Bt protein was not related to this reduced colonization. In the same study when soybean was planted on the soil with Bt maize or parental maize as previous crops no difference in colonization was observed in either case. Ren (2006) also observed adverse effects of transgenic rice on mycorrhiza in the form of a reduction in spores and mycorrhizal colonization. In case of flax that was genetically modified for disease resistance and improved fiber, no adverse effect was observed on arbuscules in most of the cases along with enhanced P nutrition, though significant mycorrhizal benefits on plant development and photosynthesis were not evident in the above study (Wróbel-Kwiatkowska et al. 2012). Since AMF support plant growth and productivity and have major role in overall fungal activity, the effect of GM plants on mycorrhizal growth and development must be taken into account while monitoring the possibility of potential hazards associated with such crops (Verbruggen et al. 2012).

15.3 Impact of Agricultural Practices and Farming Systems on Soil Health, Quality Parameters

Maintaining a healthy soil microflora and favoring the action of beneficial microorganisms has been considered as an integral part of soil quality maintenance. Microbiological parameters have been found to be more sensitive indicators to agricultural management and crop rotation systems as the presence of leguminous crops in rotation system having no tillage agricultural practice gave rise to higher MB-C and N, lower basal respiration and metabolic quotient and 24% lower ratio of soluble C & N to MB-C and MB-N which implies reduced loss of these fractions as a consequence of leaching (Franchini et al. 2007). However, Paul and Juma (1981) found that inside soil, microbial biomass resides for approximately for 1 year. In the studies of Lundquist et al. (1999) in the system having crop rotation and organic farming, despite of a considerable increase in microbial biomass, such change was consistent for only 3 weeks which makes it difficult to rely on microbial biomass as a sensitive indicator for soil quality or microbiological change.

Dick et al. (1996) considered soil enzyme important candidates for providing preliminary indication of changes in soil management practice. β-glucosidase has been known to give an early response to field management (Bandick and Dick 1999). Roldan et al. (2005) found that improved soil structure in terms of soil aggregation had higher β-glucosidase activity. Cellulose is the major carbohydrate source for soil microbes and β-glucosidase helps in its breakdown by stimulating the hydrolysis of β-D glucopyranosides and plays a crucial role in carbon cycling (Stott et al. 2009). Rotations with higher crop diversity had higher β-glucosidase to phenol oxidase ratio irrespective of added residue (McDaniel et al. 2014).

Structural change in soil microbial communities occurs as a consequence of no tillage agricultural practice due to accumulation of bacterial and fungal population at the soil surface (Helgason et al. 2009). According to Wilson 1978 in the early nineteenth century, pioneer cultivation was most responsible factor for the rise in atmospheric CO_2. Conservation tillage, on the other hand, provides better moisture conditions (Paul 2007). Under reduced tillage conditions, soil surface maintains abundant fungal biomass but bacterial population remains relatively unaffected (Frey et al. 1999). Less soil perturbation at the soil surface as a consequence of no tillage promote soil aggregation thus increasing soil carbon storage (Bell et al. 2003).

Soil organic matter becomes prone to degradations as a result of mechanical disruption of macro and microaggregates and also by the action of drying and rewetting on aggregates. However, microbial biomass dynamics are closely associated with soil redistribution by water erosion but independent of that by tillage erosion but soil organic carbon dynamics are influenced by soil redistribution by both water and soil erosion (Xiaojun et al. 2013). As studied by PLFA and DGGE Vargas Gil et al. (2011) suggested that crop rotation leads to overall enhancement in microbial and fungal communities, while fungal communities were influenced by tillage systems. Lundquist et al. (1999) found that in a 6 years old trial under organic or conventional farming having crop rotation involving tomato-sunflower-corn-wheat or legume had greater ratio of soil respiration to MBC than a frequently tilled, irrigated, and N fertilized lettuce-cole crop rotation.

A greater degree response to residue incorporation is provided by microbial community structure than by C or N pools (Lundquist et al. 1999). Under the conditions of reduced tillage, biomass produced in case of corn is more than soybean the plant residues thus left improve soil health and prevent soil erosion (Reddy et al. 2013). In the studies of Mazzilli et al. (2014) under no tillage agricultural practice comprising soybean or continuous maize, quantity of crop residues associated with greater C:N ratio were obtained in case of maize than soybean where the carbon thus derived was considered to be securely established in the mineral associated organic matter and this stabilized carbon fraction was also higher in case of maize. The combined effect of clay, slit, and other consequences of soil aggregation helps to resist the decomposition microbially derived soil organic carbon which formed inside the soil through microbial inputs (Hassink and Whitmore 1997).

A diversified crop rotation system enhances active C content and microbial biomass N particularly in recalcitrant residues and also stimulates faster decomposition of residues as compared to monoculture (McDaniel et al. 2014). Cropping system involving forage and legume cover leads to C-sequestration inside carbon containing mineral fraction (min-C fraction) to which roots particularly make a significant contribution and the min-C fraction bears more importance than particulate organic matter fraction (Santos et al. 2011). A decrement in overall microbial biomass was observed in case of reduced tillage soybean monoculture as studied by PLFA. The rotation of leguminous crops like soybean with cereal crops coupled with no tillage agricultural practices maintained abundant and diverse rhizobia with higher N_2 fixation despite of having no inoculation from last 15 years where no N fertilization was done in case of soybean (Ferreira et al. 2000). Kihara et al. (2012) identified reduced tillage and intercropping (from soybean-maize intercropping, rotation and continuous maize cropping system) and reduced tillage (from various combinations of conventional and reduced tillage systems) best systems for enhancing total bacterial and fungal richness and overall soil structure and quality improvement.

15.4 Methods Used for Assessing the AMF Biomass and Associated Soil Biochemical Parameters

For AMF biomass parameters, the analytical-based methods such as use of signature fatty acids and quantitative PCR (Based on determining gene copy number of particular AM taxa) and glomalin are being promoted due to their higher reproducibility, rapidity, and non-biasness. Recently Buyer and Sasser (2012) introduced a high throughput phospholipid analysis method using Bligh–Dyer lipid extraction which enables analysis of 96 samples in 1.5 days and further advanced the work for AM biomass where 16:w5 ester linked fatty acid (ELFA), PLFA, and NLFA can be quantified well correlated with spore density and colonization (Sharma and Buyer 2015). At molecular level due to the lack of primers qPCR method makes that difficult due to insufficient samples for genomic analysis also hinder AMF studies at molecular level (Thonar et al. 2012). Depending upon the purpose, various methods for studying the AMF biomass, glomalin, and associated microbiological parameters are being used and a list of most potential methods used for assessing these parameters is provided in Table 15.2.

15.5 Conclusion

In order to maintain adequate resident and inoculated AMF population in the soil, AMF "friendly" agricultural practices need to be adapted as AMF hyphae is prone to damage caused by practices such as tillage which disrupt the hyphal network making it non-functioning. On the contrary the agricultural practices causing less soil perturbations like no tillage maintain a stable mycorrhizal hyphal network inside soil that not only supplies nutrients to the plant but also maintains a stable soil carbon pool. The selection of an appropriate host plant does play an important role in supporting mycorrhizal population inside soil. Maize has emerged as one of the most suitable host plants supporting the growth of AMF in the soil. Plants belonging to families such as Cruciferae (Brassicaceae), i.e., mustard, cabbage, etc., have been proven to be detrimental to AMF population in the soil and hence the inclusion of such cropping sequences in crop rotation and intercropping with mycorrhizal crops must be avoided. As far as farming practices are concerned organic as well as

Table 15.2 Potential tools to assess AMF and associated microbiological parameters

Parameter	Mode	Method	Reference
Quantification of AMF biomass	Microscopic	Sucrose centrifugation for AMF spore density	Brundrett and Juniper (1995)
		Wet Sieving and decantation for AMF spore density	Gerdemann and Nicolson (1963)
		Aqueous biphasic system for AMF spore density	Salvador-Figueroa et al. (2008)
		Root staining for observing AM colonization in the roots	Phillips and Hayman (1970)
		Percent root colonization	Biermann and Linderman (1983), Giovannetti and Mosse (1980)
		Hyphal biomass (through membrane filtration)	Miller et al. (1995)
	Molecular and biochemical	AMF signature 16:1w5 phospholipid 16:1w5 neutral lipid fatty acids	Olsson et al. (1997), Sharma et al. (2012)
		Ester-linked fatty acid (EL-FAME)	Sharma et al. (2012)
		Sterols (AM signatures)	Fontaine et al. (2004)
		qPCR (based on gene copy number of AM taxa)	Alkan et al. (2006), Thonar et al. (2012)
		Glomalin	Wright and Upadhyay (1996)
Biomass carbon estimation and enzymes	Soil biochemical	Microbial biomass carbon fumigation-extraction method	Vance et al. (1987)
		Substrate induced and basal rate respiration	Anderson and Domsch (1978), Anderson (1982)
		Soil acid and alkaline phosphatase	Tabatabai and Bremner (1969)
		Soil dehydrogenase and fluorescein diacetate	Tabatabai (1994), Aseri and Tarafdar (2006)
		β-glucosidase	Tabatabai (1994)

integrated farming practices should be used as these practices not only enhance AMF population inside soil but are also least potentially harmful to the atmosphere as compared to conventional ones. One more essential component of AMF functioning is the production of carbon sequestering compound "glomalin." This compound belongs to the recalcitrant carbon pool and is also influenced by agricultural management practices like tillage as soil disturbance caused due to tillage, break the stable soil aggregates formed by the gluing action of glomalin that releases the carbon held inside these aggregates. Apart from this organic farming also enhances AMF population as well as glomalin production in the soil. This makes glomalin as important indicator of change in agricultural management practices. However, glomalin extraction from soil largely depends upon the soil type, extractant, and the methods of quantification due to interference caused by agents like polyphenols. Glomalin has also been found to give resilience to plant from factors such as drought. There are various tools to monitor AMF in soil. Methods like spore count depend on handling and also affect the viability of the spores. AMF colonization also needs expert supervision to discriminate between AMF hyphae and other fungal hyphae. Molecular methods like qPCR are skill oriented. Lack of primers is also an issue in AMF identification. Phospholipids fatty acid analysis relies on the use of signature fatty acid 16:1w5 but its presence in other microbes makes it difficult to draw the conclusion regarding the presence of microbial population on the basis of it. All such factors together make the quantification of AMF more challenging in order to examine the impact of various agricultural practices. The combination of all the approaches, i.e., microscopic, molecular, and biochemical being used to study AMF needs to be explored to get the correct trend of AMF population residing in soil as a result of different soil and nutrient management practices as well as the cropping sequence. The practices leading to minimal soil disturbance and restoration of lost SOC pool due to combined action of AMF and glomalin must be followed to create a better soil ecosystem promoting better soil health comprising less carbon emissions, having better implications on plant, human, and animal health without causing damage to the nature.

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Bioremediation of Contaminated Soils: An Overview

16

Manisha Mishra and Devendra Mohan

Abstract

Bioremediation has attracted attention of scientists and biotechnologists for environmental control and it employs biological agents mainly microorganisms like yeast, fungi, algae, or bacteria to treat contaminated soils or water derived in the process applied for treatment of such sites. Microbial bioremediation for in-situ removal of organic pollutants, heavy toxic metals, radionuclides, etc., can be applied successfully. Specific bioremediation technologies can also be developed based on toxicity of contaminants and the site conditions. As a component of bioremediation, application of plants for removal of contaminants from environment, known as phytoremediation, can also be made and hyperaccumulator species are capable of accumulating toxic metals about 100 times higher than those typically found in common plants. Uses of a number of biosorbents for soil treatment by uptake of ionic species present even up to tracer levels (around 10^{-7} M) has been demonstrated successfully. Molecular approaches can be effectively applied to enhance bioremediation. This paper presents an overview of various studies carried out on bioremediation of contaminated soils.

Keywords

Heavy toxic metals • Pollutants • Soil contamination • Bioremediation

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16.1 Introduction

A number of techniques are presently being employed to handle the case of soils contaminated with toxic materials. There are basically two aspects associated with the occurrence of metallic species in nature: toxicity and recovery. It has been known for quite sometimes that particularly heavy metals such as lead, mercury, cadmium, and chromium are toxic to humans even at relatively small concentrations. Some of these elements like lead, mercury, cadmium, and arsenic tend to get concentrated through food chain and consequently, relatively lower concentrations reaching surface waters even through contaminated soils may be subjected to bioaccumulation and biomagnifications. Ultimately, near apex of the food chain, hazardous build up of heavy metal concentrations, and other cumulative toxic compounds have been observed. Therefore, as a preventive measure, it becomes imperative to treat the wastes before discharge on land. But earlier, there have been frequent industrial practices of discharging the partially treated or even untreated liquid wastes on soils and as a consequence, sizeable amount of land still remains as barren or unproductive. Therefore, with rising population and shrinking land resources, it is required to devise appropriate treatment and safe disposal methodologies for such soils. Some of the commonly applied approaches are as follows.

(1) *Landfilling*: Excavation, transport, and deposition of the contaminated soil need to be done in a permitted hazardous solid waste landfill. Bottom of the landfill must be properly sealed to prevent any risk of leachate reaching the groundwater aquifer. Although soil removal and replacement may correct locally the adverse effects of contamination, the method is expensive or may disperse contaminants also. Many times, it results in simple movement of the contaminated soils from one site to another location.
(2) *Fixation*: Chemical processing of soils is done to immobilize the metals. It is usually followed by treatment for sealing the soil surface to eliminate any possibility of penetration by rainwater.
(3) *Leaching*: The process employs mostly acidic solutions or proprietary leachants to leach and thus, remove metals from the soil. If done ex-situ, it may be followed by return of cleaned soil residue to the original site.

Traditional approaches applied for removing contamination existing primarily in water or leached out into water from contaminated soils had included suitable combinations of various unit operations and processes like precipitation, coagulation and flocculation, sedimentation, filtration, ion-exchange, reverse osmosis, etc. But, for some time, microbes have also been applied for treatment of various environmental components including soils contaminated with heavy metals and other toxic substances. Bioremediation has emerged as one of the prospective method for large-scale applications. Popularly, the process is known as bioremediation, which may be understood as elimination, attenuation, or transformation of polluting or contaminating substances by use of biological processes. It is a relatively low-cost technique, which generally get higher public acceptance and therefore, can be classified as an on-site methodology (Vidali 2001). Bioremediation employs biological agents mainly microorganisms, e.g., yeast, fungi, algae, or bacteria, to purify contaminated soil (Strong and Burgess 2008). Parameters of critical importance for bioremediation (Dua et al. 2002) are:

(1) Nature of pollutants
(2) Soil structure, pH, moisture contents, and hydrogeology
(3) Nutritional status and microbial diversity of the site
(4) Temperature and oxidation reduction (Redox) potential.

In bioremediation processes, microorganisms consume the contaminants as their nutrient or energy sources (Tang et al. 2007). The microbial activities may also be enhanced by supplementing with limiting nutrients, electron acceptor and substrates, or by introducing microorganisms, equipped with the enzyme-system for the desired biocatalytic action (Ma et al. 2007; Baldwin et al. 2008). These processes are known as biostimulation and bioaugmentation, respectively. Microbes in the plant-soil systems may also develop a rhizospheric zone, which can also be effectively employed by them as an apparatus for accelerating rate of biodegradation for remove of the contaminant(s).

Microbial biomass and agricultural materials have been successfully employed for adsorption of toxic metals from industrial liquid wastes. The approach is more attractive than other ways of adsorption on chemical-entities because of relatively higher efficiency of metal uptake (Volesky 1987) and also, due to easy availability and consequent lower cost of the biosorbent. Biosorption was used to remove various metals from their solutions using various kinds of microbial biomass and agricultural materials. For example, Aksu and Kutsal (1991) used the biomass of *Chlorella vulgaris* to remove lead (II) ions from wastewater. Baldry and Dean (1980) have reported that *E. coli* strain FE 12/5 can uptake copper ions. As agricultural adsorbents, Tiwari et al. (1995) used rice husk ash to remove mercury (II) from aqueous solutions. Marshall and Champagne (1995) applied soybean hulls, cottonseed hulls, rice straw, and sugarcane bagasse to remove chromium (III), cobalt (II), copper (II), Nickel (II), and zinc (II) ions from aqueous solutions. Bhattacharya and Venkobachar (1984) employed coconut shells for removal of cadmium. It has been well known for many years that some microorganisms can take up large amounts of heavy metals such as copper, cadmium, lead, and uranium (Ross 1986). The majority of studies on metal uptake from solution using bacteria have used living cells, either immobilized or in suspended culture.

The bioremediation, using microorganisms to degrade pollutants in-situ, has greatly attracted field-application-oriented interest of scientists and biotechnologist in recent years. Unfortunately, toxic heavy metals and radionuclides cannot be fully stabilized chemically and therefore, application of microbial bioremediation for in-situ removal of heavy metals from contaminated sites is mostly limited to their immobilization by precipitation through oxidation or reduction processes. The abilities to tolerate both, elevated levels of heavy metals, and also to accumulate them to unusually high concentrations have evolved independently as well as simultaneously in a number of different plant species (Baker et al. 1989). Accumulators of Ni, Co and Cu (Baker 1981), Pb and Zn (Reeves and Brooks 1983), and Se (Banuelos et al. 1993) have already been reported in detail.

As a component of bioremediation, application of plants for removal of contaminants from environment is also known as phytoremediation. Phytoremediation of heavy metals may be divided into the following groups:

1. *Phytoextraction*: The metal accumulating plants are used to transport and concentrate metals from the soil into the harvestable parts of roots and above ground shoots or leaves (Kumar et al. 1995).
2. *Rhizofiltration*: Plant roots are employed to absorb, precipitate, and concentrate toxic metals from the polluted effluents (Baker et al. 1994). It may be employed serve as a water purification or marsh-remediation technique.
3. *Phytostabilization*: The plants, tolerant to toxic heavy metals, are applied to reduce the mobility and migration of heavy metals, thereby reducing the risk of further environmental degradation on account of leaching into groundwater or by airborne spread. Leachable constituents are adsorbed and bound into plant structure to form a stable mass of plant from which contaminants will not be able to re-enter the environment easily.

The heavy metal contaminations of soils have been linked to the disruption of natural ecosystems. In particular, excess Cd in soil has been the cause of human health effects, and excess Zn has injured plants and caused animal fatalities. In the majority of cases, severe metal contamination of soils is the result of human activities. Effective technologies for the remediation of metal contaminated sites in-situ do not currently exist. Problems associated with the heavy metal contamination of soil have been well documented. In particular, excess Cd and Zn in soil have been the cause of human health effects, animal fatalities, and the disruption of natural ecosystems (Malik 2004). Although soil contamination may also be geochemically derived (calamine and other mineral-rich soils), it is often an unintentional consequence of anthropogenic activities. Though consequences of contaminations are better understood now, effective and economic technologies for remediation of the sites remain still elusive (Hiroyuki 2009).

For bioremediation of contaminated soils, there have been a number of attempts with diverse approaches. Yanga et al. (2015) studied a biosurfactant producing bacterial strain with capacity of alkaline production, which was isolated from cafeteria sewer sludge and its capability for removing Zn, Pb, Mn, Cd, Cu, and As was investigated. The removal efficiencies were found to be 44.0% for Zn, 32.5% for Pb, 52.2% for Mn, 37.7% for Cd, 24.1% for Cu, and 31.6% for As. In another study, a pot experiment with 16 treatments was carried out to assess possibility of using Silkworm excrement and mushroom dregs to stabilize heavy metals and metalloids and reduce their uptake in pakchoi cultivated in slightly contaminated soils with arsenic (As), cadmium (Cd), lead (Pb), and zinc (Zn). The results showed that it simulated growth of the vegetable and also reduced contents of the heavy toxic metals and metalloids in edible parts of the plant (Wang et al. 2015).

An investigation on feasibility for in-situ electrokinetic remediation in case of toxic metal contaminated soils driven by microbial fuel cell (MFC) was conducted. With electric current generated through oxidation of organics by microorganisms, the metals in the contaminated soils would be removed. Concentrations of Cd and Pb in the soils increased gradually from anode region to cathode region after bioremediation. After an operation for 108 days, removal was 44.1% for Pb and after 143 days operation; removal was 31% for Cd around the anode region (Habibula et al. 2016). Another study showed more than 97.0% of Cu and higher than 87.0% of Zn recovery from acidic mine drainage by bioremediation. Using bioremediation, recovery of valuable metals from acidic mine drainage using straw based system was investigated and the process was observed to be efficient for metal recovery (Lu et al. 2012).

Other studies involving natural attenuation, biostimulation, and bioaugmentation of microorganisms, removal of nitrobenzene from contaminated sediments was carried out and compared. Within 10 days, 6 mg/kg of nitrobenzene from the sediments and 53 mg/L of the same compound from the water were biodegraded by Pseudomonas putida, which was isolated from the contaminated sediments (Ibrahim and Gamila 2009).

Recently, molecular approaches are also being applied to enhance bioremediation. Current developments are taking place in bioremediation by utilizing rhizoremediation, protein engineering, metabolic engineering, whole transcriptome profiling, and proteomics for degradation of recalcitrant pollutants such as chlorinated aliphatic and polychlorinated biphenyl as well as for binding heavy metals (Wood 2008). Cell surface expression of specific proteins allows the engineered microorganisms to transport, bioaccumulate, and/or detoxify heavy toxic metals as well as to degrade xenobiotics (Arshad et al. 2007).

16.2 Methods of Bioremediation

Removing toxic heavy metals at very low concentrations (submicron/tracer levels) is quite intricate. Chemical precipitation, reverse osmosis, and many other commonly applied methods become inefficient at trace concentrations. In such situation, adsorption may be one of the few effective alternatives. To achieve this purpose, works on many conventional adsorbents have been done, i.e., activated carbon, activated alumina, and ion-exchange resin (Volesky 1987) to quote just a few.

The potential of living or dead microorganisms to accumulate heavy metals has been well documented (Mishra et al. 1998a, b). Usually perceived benefits of dead organisms are that they need no sustenance from the contaminated streams, but obviously, they are non-regenerative and therefore, cannot metabolize the contaminants. As waste streams are frequently contaminated with a cocktail of organic and inorganic chemicals, of which metals may be only one constituent, the ability to co-extract more than one pollutant can be of significant process advantage (Mishra et al. 2006). An active agent of biological origin, popularly called biosorbent, which can be used for the recovery of metals must meet the following criteria (Mishra 1998).

1. Need to be produced at a lower cost and should also be preferably reusable.
2. Uptake of the metal should be effective and rapid.
3. Should have proper particle size, shape, and mechanical properties for use in continuous-flow in packed bed or fluidized bed systems.
4. Separation of the contaminant-laden biosorbent must be low cost, efficient, and rapid.
5. The sorbent should be selective in order to separate the target metal from other species.
6. Separation of metal from biosorbent should be metal selective and economically feasible with the minimum feasible loss of biosorbent.

16.3 Bioremediation Using Microorganisms

Bacteria are the most abundant and versatile of all the microorganisms (Ferris and Beveridge 1985) and constitute a significant fraction of the entire living terrestrial biomass (~10^8 g). High capacity for biosorption of heavy toxic metals by microorganisms has been known for some time, i.e., Pb and Cd can be bioaccumulated in marine microorganisms by a factor as high as 1.7×10^5 in comparison to aqueous concentrations of these elements in ocean water (Fairbridge 1972).

Cd, like lead and tin, is toxic in the cationic state; while cadmium, like mercury, tends to be more toxic in methylated form (Weed 1983). The alkyl forms of these metals are sufficiently stable to be detected in laboratory. Many Cd^{2+}-sensitive strains of bacteria possess a high capacity for the accumulation of Cd^{2+}, whereas Cd^{2+}-resistant strains have the ability to prevent intracellular accumulation. Sulmon et al. (1971) have described decreased uptake of cadmium by a resistant strain of *Staphylococcus aureus*, relative to cadmium-sensitive organisms, which accumulated approximately 40% of radioactively labeled Cd^{2+} ions or about 15 times more the amount taken up by the resistant organism. Mitra (1984) conducted extensive studies on inhibitory effect of Cd^{2+} on the growth of *E. coli* and *Pseudomonas putida*, as well as the molecular mechanisms of accommodation during recovery from toxic levels of this ion, which appears to be associated with Cd^{2+}-binding proteins that may modify availability of the ion as well as its potential toxicity (Highman and Sadler 1984). This mechanism is distinct from the mode of Cd^{2+} resistance reported for *S. aureus* which involves exclusion of Cd^{2+} and is accomplished through an energy-dependent efflux system. Titus et al. (1980) have demonstrated that cadmium uptake by a *Pseudomonas sp.* was greater than that of an artificial sediment.

Micrococcus luteus and *Azotobacter sp.* cells capable of immobilizing 4.9 and 3.1×10^2 mg of lead per gram of dry cell weight, respectively, have been described by Tornabene and Edwards (1972). The lead caused no toxic effects on growth and reproduction and about 99% of the metal was found in the cell wall and membrane.

The remaining small percentage (1%) was observed to get associated with the cytoplasm. Immobilization and bioaccumulation of lead by bacteria may result in the transfer of the metal through the food chain to animals and man.

Certain metals like zinc, copper, nickel, and chromium are essential micronutrients for plants, animals as well as microorganisms (Olson et al. 2001); while a few others (cadmium, mercury, arsenic, and lead) have no known biological and/or physiological beneficial function (Gadd 1992). Rather, higher concentrations of these metals exert greatly adverse effects on the microbial communities in several ways as follows: *(1)* it may lead to reduction of total microbial biomass (Giller et al. 1998), *(2)* it may result in decrease in number of microorganisms in a specific species, or *(3)* it may alter microbial community structure altogether (Gray and Smith 2005). Thus, at higher concentrations, metal ions can either completely inhibit the microbial population by inhibiting their metabolic activities like protein denaturation, inhibition of cell division, cell membrane disruption, etc., or otherwise, organisms can develop resistance or tolerance to elevated levels of metals.

Ex-Situ Bioremediation of Soil: This approach can be faster, easier to control, and can be used to treat a wider range of contaminants and soil types than in-situ techniques. However, they require excavation and transportation of the contaminated soil before and after the bioremediation step. It includes commonly used slurry-phase bioremediation as described further.

In *Slurry-phase bioremediation*, contaminated soil combined with water and other additives is mixed thoroughly to maintain the microorganisms in almost uniform distribution and close contact with contaminants in the soil. All this is placed and stirred in a large tank called bioreactor. Conditions in bioreactor are appropriately controlled to ensure an optimum environment for microorganisms to degrade the contaminants. After treatment of the soil, water is removed, which may be disposed off directly or treated further according to the prevailing environmental control regulations.

16.4 Application of Microorganisms to Enhance Uptake by Plants

Soils contaminated with heavy metals are usually deficient in established vegetation cover due to toxic effects of pollutants. Barren soils are more prone to erosion and leaching, which can further spread pollutants far and wide. A feasible solution to the stabilization of such wastes is to develop vegetation cover with the toxic metal-tolerant plant species. Use of plants in combination with microorganisms to biodegrade the pollutants under mostly uncontrolled field conditions has also been reviewed earlier (Bartlett and James 1979).

It is worth mentioning that application of microorganisms to improve the uptake of heavy toxic metals by plants from soils has not been fully explored. It is known that plant uptake of certain mineral nutrients such as Fe (Crowley et al. 1991) and Mn (Barber 1974) may be facilitated by rhizospheric microorganisms. A number of microorganisms isolated (in nutrient cultures) from heavy metal contaminated soils have been observed to stimulate metal uptake by plants. Therefore, it may be understood that by populating the rhizosphere with the selected microorganisms during the processes of phytoextraction and rhizofiltration, it may be feasible to increase the uptake of heavy toxic metals from soils or aqueous streams. Specially selected microorganisms can be applied to the plant-soil system through seed treatment or these may also be added in irrigation water (Sulmon et al. 2007).

For enhancing the performance under toxic heavy metal-rich environment, plant growth promoting rhizobacteria have evolved numerous mechanisms through which they can immobilize, mobilize, or biotransform the metals. These mechanisms include: *(1) exclusion*—the metal ions are kept away from the target sites, *(2) extrusion*—the metals are pushed out of the cell through chromosomal/plasmid mediated sequence of events, *(3) accommodation* of metal-complex with the metal-binding proteins (e.g., metallothioneins, low molecular weight proteins) (Kao et al. 2006; Umrania 2006) or other cell components, *(4) bio-transformation*—toxic metals are converted to relatively less toxic forms, and *(5) methylation* and *demethylation*. These mechanisms can make them capable of not only tolerating, but also carrying out the uptake of heavy metal ions and toxic substances effectively.

16.5 Heavy Metal Resistance in Plants

Metals in the soil environment may exist in several forms as follows: *(1)* free metal ions and soluble metal complexes in the soil solution, *(2)* metal ions occupying ion-exchangeable sites and specifically adsorbed on inorganic soil constituents, *(3)* organically bound metals, *(4)* precipitated or insoluble compounds, particularly in the form of oxides, carbonates, and hydroxides, and *(5)* metals in structure of some silicate minerals. Anthropogenic metal contamination of soils normally results in metals occurring in one or more of the above-mentioned forms (Nriago 1979; Settle and Patterson 1980). Metals present in fractions may be indicative of background or indigenous soil concentrations (Summers 1992).

The evidence for evasion of heavy metal toxicity by reduced cellular uptake is very incomplete. Nevertheless, avoidance may also be an available strategy for certain sensitive tissues like the root-tip meristem. Some plant ecotypes, endemic to heavy metal polluted soils, have been shown to contain heavy metal resistant enzymes, e.g., cell wall acid phosphatases. However, it is quite improbable that development of heavy metal resistant biochemical processes might be a viable heavy metal resistance mechanism. If heavy toxic metals happen to accumulate within cells, these need to be detoxified. This may come about through a number of routes through chelation, compartmentalization, or precipitation depending on the metal (Danika and LeDuc 2005).

16.6 Bioremediation by Hyperaccumulators

Higher plant-assisted bioremediation or phytoremediation is usually involves application of terrestrial green plants for treating soils, polluted with chemicals or radioactive nuclides (Raskin and Ensley 2000). Recent reports describe development of some transgenic poplars (*Populous*) over-expressing a mammalian cytochrome P450, a family of enzymes normally responsible for metabolism of the toxic compounds. The engineered plants showed enhanced performance for removal of a range of toxic volatile organic pollutants. It has been suggested that transgenic plants might be able to contribute to much wider and safer applications of phytoremediation (Frerot et al. 2006). Phytoremediation of herbicides has also been studied using conventional plants (Hiroyuki 2009).

Phytoextraction (or phytoaccumulation) employs plants or algae to remove contaminants from soils, sediments, or water into harvestable plant biomass. This has been growing rapidly in applications globally for more than the last three decades (Sulmon et al. 2007). One of the major advantages of phytoextraction is that it is relatively more environment-friendly. This technique brings down the remediation cost remarkably by accumulating even lower concentrations of contaminants from an area, geographically widespread.

In case of organic pollutants, such as pesticides, explosives, solvents, industrial chemicals and other xenobiotic substances, certain plants, such as canas, render these substances non-toxic by their metabolism. In other cases, microorganisms living in plant-roots in symbiotic relationship may help to metabolize toxic substances in soil or water. These complex and recalcitrant compounds cannot be broken down to stable small molecules by plants and therefore, the term *phytotransformation* is frequently used to stand for changes in chemical structures without complete stabilization of toxic compounds. It denotes the uptake of organic contaminants from soils, sediments, or water and subsequently, their transformation to more stable, less toxic, or less mobile form.

Hyperaccumulators are normally recognized as species capable of accumulating toxic metals at levels about 100 times higher than those typically found in widespread non-accumulator plants. Thus, a hyperaccumulator can concentrate more than 10 ppm Hg, 100 ppm Cd, 1000 ppm Co, Cr, Cu and Pb and 10,000 ppm Ni and Zn. By now, around 400 plant species from at least 45 families have been identified to hyperaccumulate toxic metals. Best known metal hyperaccumulator is *Thlaspi caerulescens* (alpine pennycress). Soil remediation using this technology involves removal and replacement of contaminated soils (Gieger et al. 1993). An alternative soil remediation technique has been proposed that uses rare, heavy-metal-tolerant plant species, which are efficient in hyperaccumulation of toxic heavy metals in plant shoots (Chaney 1983). These tolerance mechanisms may be utilized to remove heavy metal pollutants from soils (Chaney 1983). This proposed technology, called phytoremediation, involves successive croppings of hyperaccumulator plants to translocate polluting metals from soil to plant shoots. Shoots of some species accumulate as much as 4 g Ni or Zn per kg of dry biomass and consequently, the plant ash becomes comparable to low-grade metal ores (Baker and Walker 1990). Harvested plant shoot biomass can be processed to recover the accumulated metal.

It has been observed that metal adsorption in soils is dependent strongly on pH (McBride and Blasiak 1979). For phytoremediation to be successful, it is also crucial to identify quantitative relationships linking soil metal concentrations with the plant uptakes. If uptake can be increased by lowering the soil pH to enhance metal-solubility, number of croppings required to take away toxic metals may be brought down significantly.

Hyperaccumulation is often associated with relatively slow growth rates. Hyperaccumulation is a three stage process involving uptake by roots, transport to shoot, and sequestration of metals within the shoot. Reeves and Brooks (1983) observed that *T. caerulescens* can make use of a fraction of the soil Zn pool that is not phyto-available to most of the usual species, but no labile Zn comparisons were made. Another important characteristic of hyperaccumulator species is that they exhibit shoot/root ratios of metal contents always greater than one (Baker 1981). This indicates that some specific internal system may be working to pump metals up from plant roots to shoot tissues. A laboratory study showed that as Zn concentrations in solution increased beyond certain limit, value of shoot/root Zn ratio reached below one. This may suggest that certain segments of the hyperaccumulator mechanism are less effective as soil solution Zn concentrations increase.

Thlaspi caerulescens has been identified as a Zn and Ni hyperaccumulator (Rascio 1977). *Bladder campion* has ecotypes that are able to tolerate a variety of metals and falls under the indicator plant classification (Baker et al. 1983). Though *Bladder campion* is not an appropriate plant for phytoremediation, its higher Zn and Cd tolerance allows it to be applied as a befitting species for recolonization and stabilization of contaminated sites (Prasad 2004).

16.7 Rhizoremediation

Rhizoremediation involves removal of particular contaminants from waste at the contaminated sites by mutual interaction of suitable microbial flora and plant roots. *Pseudomonas putida* KT2440 is a root colonizer having great potential for application in rhizoremediation of certain pollutants as well as biocontrol of pests (Lazaro et al. 2000). It has also been hypothesized that when an appropriate rhizosphere strain is used with a suitable plant, the bacteria may also inhabit the root-zone together with the indigenous microbial population and thus, can significantly enhance the process of bioremediation.

Rhizoremediation of heavy metal-contaminated soils can thus prove to be of noteworthy economic value as such soils occupy sizeable areas, which have remained unfit for sustainable agriculture. To surmount the inherent limitations of the detoxification capabilities, plants have been genetically modified, applying an approach analogous to development of transgenic crops for about last two decades. In higher plants, bacterial genes encoding enzymes responsible for breakdown of explosives like nitroreductase and cytochrome P450 have also been introduced, leading to considerable improvements of tolerance, uptake, and detoxification performances in plants (Prasad 2004).

16.8 Using Biomass for Remediation

Application of a variety of biosorbents for bioremediation through uptake of ionic species even up to tracer level (around 10^{-7} M) has been demonstrated in controlled laboratory conditions. This prompted research to make novel uses of certain biomasses/biomolecules like rice husk, mango bark, neem bark, and casein for removal of heavy metal toxic ions (Cd^{2+}, Hg^{2+}, Zn^{2+} and Cr^{2+}) from simulated aqueous wastes (Mishra 1998). The uptake behavior of milk protein (casein) for some heavy metal ions (Cd^{2+}, Hg^{2+}, and Cr^{2+}) was investigated using radiotracer techniques. Effects of various physico-chemical treatments have also been investigated in order to explain the sequestering behavior of this biomass (Mishra et al 1998a, b; Mishra 2007a, b, c).

Superiority of non-viable biomass of *Pseudomonas* in Ni sorption (60%) over either the cyanobacterium *Nostoc* (41%) or the non-sulfur bacterium *Rhodospseudomonas* (35%) have been demonstrated and it has been found that application of such biosorbents has potential for metal removal. Effective degree of Ni remobilization by non-living biomasses derived from cyanobacteria like *Rivularia* (40%) or *Aphanothece* (30%) have been observed (Asthana et al. 1995). The non-viable biomasses derived from algae like *Sargassum* and *Ascophyllum* and fungus *Saccharomyces cerevisiae* have been useful in the biorecovery of Cu, Cd, Zn, and U (Kuyucak and Volesky 1988). Differences in metal removal capacities of such biological systems have been ascribed to cell wall chemistry and/or concentrations of cellular exopolysaccharides (Beveridge 1989).

Removal of heavy toxic metals by microbial cells has been identified as a prospective substitute to existing technologies employed for recovery of the metals from natural waters as well as industrial or urban waste streams (Barkley 1991). Microorganisms can amass metals through their metabolism-dependent uptake systems (Brierly 1990) or by adsorption onto cell-wall surfaces and external envelopes (Fourest et al. 1991). Earlier studies have revealed that adsorption of toxic heavy metal cations by microorganisms is mostly a rapid and reversible reaction, which is not mediated by metabolic processes (Greene et al. 1987). It has been found experimentally that dead cells can build up heavy toxic metals almost to the same degree or even to a greater extent in comparison to the living cells (Aksu and Kutsal 1991).

For about the past two decades, potential of metal biosorption has been ascertained quite well. For economic reasons, of higher interest are abundant biomass types, generated either as waste by-products of large-scale industrial fermentations or certain metal-binding algae, growing abundantly in the sea. Some of these high metal-sorbing biomass types may be effectively employed for novel metal biosorption processes, which may be predicted as quite competitive approaches for detoxification of metal-bearing industrial effluents and also for bioremediation of contaminated soils.

The activated sludge treatment employs a large community of microorganisms, which are continuously supplied with organic matter and oxygen (Verstraete and Van Varenbergh 1986). Most of the microorganisms present are bacteria, but many other organisms such as cyanobacteria, fungi, yeasts, algae, and ciliates have also been observed to play significant roles (Adams and Sanders 1985). The microflora consume the organic matter and convert it by means of aerobic metabolism into another type of microbial biomass, carbon dioxide, water, and minerals. Heukelekian and Schulhoff (1938) identified two processes in activated sludge process, i.e., oxidation and floc formation, and proposed that different microorganisms may be involved in these two processes. Various studies have shown that considerable quantities of toxic heavy metals present in settled sewage may be taken out using biological treatment based on activated sludge process (Oliver and Cosgrove 1974) before application of the sludge on soils as manure.

Some biosorbents have been observed be active on a "wide-range" binding many heavy metals with no specific priority, while others were found to be specific for certain metallic species. When considering adverse environmental impacts of heavy metal toxicity, the "big three,", mercury, lead, and cadmium have remained for long in the focus (Volesky 1987). Microorganisms also influence redistribution of metals by oxidation and reduction or by binding and this can serve for further metal exploration (Carlisle et al. 1986). Both oxidation and reduction reactions are of primary importance in redistribution of metals (Ehrlich 1978). The transformations of some non-toxic elements that serve as energy sources for the concerned bacteria carry substantial economic significance in connection with recovery of metals from low-grade ores and these are also of high ecological importance on account of strong acidification of mine wastewaters (Brierly 1977), which largely damages the receiving water bodies as well as the soils coming in its contact.

16.9 Concluding Remarks

Pollution of soils with toxic heavy metals and other pollutants has been accelerated due to increase in population, rapid industrialization, and other anthropogenic activities. This type of pollution in water and soil has emerged as one of the major environmental challenges, which adversely affect the growth and metabolism of plants, animals, and human beings. Realizing hazardous implications of such toxic materials in environment, this paper presents an overview on various aspects related to bioremediation using microbes and some biosorbents. Some approaches involving molecular engineering are also being applied nowadays to enhance bioremediation.

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Bioremediation of Soils Contaminated with Ni and Cd: An Overview

17

Amitava Rakshit, Sumita Pal, Manoj Parihar, and H.B. Singh

Abstract

Environmental pollution due to heavy metals (HM) is a concern globally since this may lead to geoaccumulation, bioaccumulation, and biomagnifications in ecosystems as they can penetrate the food sequence via anthropogenic actions such as continuous addition of waste water, sewage sludge application, and purification of metals. These metals have been widely studied and their effects on soil-plant-animal continuum regularly reviewed with varied perspective. In the present review, we sum up contemporary knowledge about bioremediation of heavy metals in particular nickel (Ni) and cadmium (Cd) which are potential soil and water pollutants. Among the different bioremediation options available phytoremediation emerges as a sustainable and inexpensive technology. On the other hand, as phytoremediation is a dawdling process, enhancement of efficiency and for augmented stabilization or removal of HMs from soils arbuscular mycorrhizal (AM) fungi afford a smart system to press forward plant-based environmental clean-up.

Keywords

Bioreclamation • Plant • Microorganism • Heavy metal • Ecosystem

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17.1 Introduction

Environmental pollution is one of the prime concerns of today's society. The huge amount of organic and inorganic wastes generated annually in the materials cycle and the improper disposal practices used have ended in a worldwide problem. Most important sources are the smoldering of fossil fuels, withdrawal and smelting of metalliferous ores, agrochemicals, and urban wastes. Apart from this, natural mineral deposits containing outsized quantities of HMs are found across diverse ecological regions (Hogan 2010). The entry of pollutants into the recipient ecosystems has clearly beleaguered their self-cleaning capability and, as an outcome, resulted in the buildup of pollutant. These contaminants have accelerated dramatically since the Industrial Revolution pose serious ecological threats to natural ecosystems with fatal consequences for environmental quality, sustainable food production, and human health (Lili et al. 2013). Among pollutants, contamination through HMs and metalloids is a serious problem throughout the world at many polluted spots. In India the most frequently occurring metals or metalloids at these sites are arsenic, lead, chromium, copper, zinc, cadmium, nickel, and mercury.

Among the HMs Ni and Cd are major ecological pollutants deriving from both point and non-point. The chemical variety of these metal pollutants influences its solubility, transportability, and toxicity in soil-water-plant systems which depend on the supply of the metal waste, soil, and groundwater chemistry at the location. The biological effects of HMs in soil are intimately associated with the allocation of species in the solid and liquid phase of the soil. A complete understanding of the connections between the HMs and the soil matrix is requisite to arbitrate their environmental impact as well as remediation strategy.

17.2 Fate of Ni and Cd Metals in Soils

Within the group of heavy metals Ni and Cd have a high relevance in contamination processes. These are metals with a density higher than 5×10^3 kg m^{-3}, high atomic number (>20) and atomic mass. These metals are present in soils as a result of both geogenic and anthropogenic activities. At present, however, the release into the environment is mainly due to human activities that include among others: agriculture (fertilizers, pesticides, etc.) and metallurgical activities (mining, smelting, metal transformation and finishing, etc.). Unlikely organic contaminants these metals cannot be degraded neither biologically nor chemically although can be transformed into other forms with different oxidation state and level of concentration. In the succession of heavy metals in the six primary terrestrial ecosystems the content of metals builds up the length of the trophic chain.

The bioavailability and mobility of Ni and Cd is highly dependent on the mechanisms associated with Ni and Cd adsorption–desorption and its kinetics in soils. Nickel is present in all known soil profile as a product of the weathering of the parent rock with an average concentration of 20–30 ppm, sometimes exceeding 10,000 ppm in some clay and loamy soils produced from weathering of basic igneous rocks and ultramafic rocks (McGrath 1995). Nickel adsorbs both on inorganic and organic ligands. Ni is not likely to precipitate as CO_3^{2-}, PO_4^{3-}, SO_4^{2-}, X (F^-, Cl^-, NO_3^-, Br^-, I^-) and oxides (Fe, Al, Ca) in soils. Nevertheless under alkaline condition (pH>9) it precipitates as Ni $(OH)_2$. $NiCO_3$ (≈100 mg L^{-1}) is the least soluble Ni salt at STP. Soil reaction is the most imperative factor controlling nickel dynamics in *soil-water-plant* system followed by soil organic matter content, $CaCO_3$ content, and sesquioxide (R_2O_3: R=Fe, Al) (Mellis et al. 2004). The solubility, sorption, and mobility of nickel amplify with decreasing pH (Kabata-Pendias and Mukherjee 2007; Tye et al. 2004; McGrath 1995). Nickel is somewhat weakly sorbed to clay and iron manganese minerals as compared to Cd and Zn (McGrath 1995). Nickel adsorption through complexation onto hydroxides of Fe and Al and chelates (organic matter, chelate bound Ca, EDTA) by the formation of a strong complex resulting Ni retention is highly pH dependent (Uren 1992; Estan et al. 1987; Businelli et al. 2004). Contrary to the above findings, Bowman et al. (1982) concluded that there was no sufficiently complete evidence of connection between Ni sorption and soil properties. Thus, it emerges that Ni will be retained in soil through the non-specific and specific adsorption.

Cd never occurs naturally in the elemental form, it is found in combination with S^{2-}, CO_3^{2-}, CO_2. The concentration of Cd in soil depends on parent material, the external addition through inorganic inputs or amendments, physical and chemical properties of soil (texture, leaching, pH, organic matter, CEC, carbonate minerals, redox potential), and pre-treatment technologies of wastes before dumping into soil. The most frequent forms of cadmium comprise of Cd^{2+}, $[Cd(CN)_3]^-$, or $Cd(OH)_2$ (Smith et al. 1995). Increase in pH results in higher adsorption of Cd. Hydroxide ($Cd(OH)_2$) and carbonate ($CdCO_3$) solids dictate at high pH whereas Cd^{2+} and aqueous sulfate species ($CdSO_4$, $CdSO_4 \cdot H_2O$,$3CdSO_4 \cdot 8H_2O$) the leading forms of cadmium at lower pH (<8). Under waterlogged conditions, when sulfur is present as S^{2-}, the steady solid CdS is formed which manage the mobility. In a nutshell pH, CEC, specific surface area and nature, and amount of organic ligands (humic and fulvic acid) are positively correlated with Cd retention whereas free iron oxides were negatively correlated (Tyler and McBride 1982; Christensen 1984; King 1988; Jopony and Young 1994; Sidle and Kardos 1977; Korte et al. 1976; Amacher et al. 1986). The clay content, specific surface area, free iron oxide content, and free carbonates were successfully used to predict Cd dynamics using computational approach (Korte et al. 1976). Precipitation of Cd occurs in the presence of phosphate ($K_{sp} = 2.53 \times 10^{-33}$), arsenate ($K_{sp} = 2.33 \times 10^{-33}$), sulfide ($K_{sp} = 1.0 \times 10^{-27}$) chromate, and other anions (oxalate, iodate), although solubility will differ with pH and other physical and chemical factors as well as on temperature and pressure (Alloway 1995).

17.3 Remediation of Metal Contamination

HMs are comparatively immobile in subsurface systems as a consequence of precipitation or sorption reactions. This prompted remediation tricks at contaminated sites paying attention on the solid-phase sources of metals. A variety of technologies is on hand for remediation with generalized approaches which include isolation, immobilization, toxicity reduction, physical separation, and extraction. These broad approaches can be used for a variety of contaminants but the exact technology preferred for treatment of a contaminated location will depend on the form of the contamination and distinctive characteristics of the site. Customary physicochemical processes for remediation are costly and often do not permanently ease the pollution vulnerability. Again a number of the existing technologies have been verified in full-scale applications and are commercially available at the moment. Quite a few biotechnologies are being attempted for application to metals-contaminated sites. Moreover one or more of these approaches of biological origin are often collectively tested for more cost-effectiveness. Within the umbrella of biotechnology bioremediation is a broad concept that comprises of all those processes and measures that take place in order to biotransform an environment, already distorted by contaminants, to its original standing and restore ecological balance. Bioremediation utilizes principally microorganisms or microbial processes to degrade and alter environmental contaminants into safe or less deadly forms (Kumar et al. 2009). In this context, phytoremediation is also emerging as a green technology which is recently being considered as highly promising for the remediation of contaminated sites. The following section summarizes bioremediation technologies for Ni and Cd contaminated soil.

17.3.1 Biological Treatment

Biological treatment technologies are accessible for remediation of metals-contaminated sites. Apart from remediation of organic contaminants these technologies are also used for metal remediation as well both at the bench scale and pilot studies (Schnoor 1997). Biological treatment makes use of usual biological processes that permit certain plants and microorganisms to assist in the remediation of metals (Rakshit and Ghosh 2009). These processes ensue through a multiplicity of mechanisms, including sorption, redox reactions, and methylation (Means and Hinchee 1994).

17.3.1.1 Bioaccumulation

Bioaccumulation involves the uptake of metals from contaminated medium by living organisms or dead, inactive biomass and active plants as an outcome of normal metabolic processes via ion exchange at the cell walls, complexation reactions at the cell walls, cell surface, or intra- and extracellular accumulation and precipitation and chemical transformations such as oxidation, reduction, methylation, demethylation. In principle biomass accumulation has been shown to be as efficient as some exchange resins sorbs free metal ions from soil water (Means and Hinchee 1994). Passive mechanisms of metal binding are attained either through extracellular complexation of metal by substances excreted by cells or binding of heavy metals to active groups of chemical compounds of cell walls and membranes.

17.3.1.2 Phytoremediation

Phytoremediation refers to the use of plants for eliminating soil contaminants where capability of plants have been illustrated as solar-driven pumping place (Cunningham et al. 1995; Pal et al. 2013) which in reality can wipe out these contaminants from the environment. A number of plants have developed the skill to eliminate ions selectively from the soil to regulate the dynamics of metals in the belowground and aboveground fractions. Most metal uptake occurs in the underground part of the plant system, typically via absorption, where numerous mechanisms are existing to avert metal toxicity due to high concentration of metals in the soil. Plants can accumulate Ni that are indispensable for growth and development and also some extent Cd that have no recognized biological role (Brooks 1998). The phytoavailability of nickel has been interrelated with free nickel ion activity in soil solution and subsequently plant uptake also depends on soil chemical properties such as soil pH, organic matter, and Fe/Mn oxide content (Kabata-Pendias and Mukherjee 2007; Tye et al. 2004). Plants are reported to take nickel more willingly in its simple ionic form (Ni^{2+}) than as inorganic, organic complexes, and inorganic–organic coordination complexes (Kabata-Pendias and Mukherjee 2007). Plant species as well as cultivars of same plant also differ in their tolerance and capability to take up nickel from soil. Plant families that have been reported for their tolerance to, and hyperaccumulation of, nickel include Brassicaceae and Fabaceae (Kabata-Pendias and Mukherjee 2007).

The phytoavailability of Cd which shows strong sorption characteristics in soil compared to Ni depends on the nature of the chemical alliance between Cd with the organic and inorganic ligands, soil pH and the capacity of the plant to regulate the uptake of Cd. The residence times of Cd soil is over 1000 years whereas mean residence time of nickel in soil of 2400 years. Phytoremediation is a novel technique to clean up contaminated soils and which offers the benefit of being in situ, low cost, and environmentally sustainable and has recently become a tangible alternative to traditional methodologies. Potentially useful phytoremediation technologies for remediation of metals-contaminated sites include phytoextraction, phytostabilization, and rhizofiltration.

Phytoextraction is one of the phytoremediation tactics based on the use of green plants to take out heavy metals from soil and its competence depends on the chemistry of the element re-moved and its intrinsic capability to distribute in shoots and roots (Table 17.1). Phytoextraction employs hyperaccumulating plants which can accrue 10–500 times higher levels of elements than normal crops (Chaney et al. 1997) and with the ability to yield at exceptional concentrations of HMs (0.1% of Ni and Cd). The aboveground shoots can be harvested to get rid of metals from the site and then disposed as hazardous waste or treated for the revival of the metals. Following the success achieved through the application of certain chelates to the

Table 17.1 Phytoextraction potential of different crop species

Reference	Plant species	Mechanism
Chandra and Yadav (2011)	Common reed (*Phragmites communis*), Cattail (*Typha angustifolia*), and Nut grass (*Cyperus esculentus*)	Noteworthy amplification of biomass and stress protein
Yang et al. (2001)	Tall wheatgrass (*Agrogyron elongatum*)	Liberation of organic acids [RCOOH: Malic (pKa = 3.4), oxalic (pKa = 1.2) and citric acids (pKa = 3.1)]
Manousaki and Kalogerakis (2009)	Mediterranean saltbush (*Atriplex halimus* L.)	Guaiacol peroxidase activity articulating oxidative damage
Paz-Alberto et al. (2007).	Vetiver grass (*Vetiveria zizanioides* L.), cogon grass (*Imperata cylindrica* L.), and carabao grass (*Paspalum conjugatum* L.)	Highly extensive root system and plants' total biomass/ principle of exclusion
Abdul et al. 2006)	Silver Philodendron (*Scindapsus pictus* var argyaeus)	Glutathione ($C_{10}H_{17}N_3O_6S$), a precursor of phytochelatin synthesis: metal detoxification and protection of intrinsic oxidative stress reactions
Amin (2011)	Corn (*Zea mays*)	Plant root exudates and rhizosphere microorganisms
Doaa (2011)	Water hyacinth (*Eichhornia crassipes* (Mart.) Solms.)	Adsorption to the anionic sites in the cell walls/exclusion approach
Lai and Chen (2005)	Rainbow pink (*Dianthus chinensis*)	Root exudates

(continued)

Table 17.1 (continued)

Reference	Plant species	Mechanism
Odjegba and Fasidi (2004)	Water cabbage (*Pistia stratiotes*)	Translocation factor = $Concentration_{shoot}/Concentration_{root} > 1$
Cluis (2004)	Candargy (*Alyssum lesbiacum*)	
Sun et al. (2009)	Hairy beggarticks (*Bidens pilosa*)	
Cluis (2004), Banasova and Horak (2008)	Alpine Pennygrass (*Thlaspi caerulescens*)	
Liu et al. (2009)	Japanese honeysuckle (*Lonicera japonica*)	
Sun et al. (2008)	Black nightshade (*Solanum nigrum* L.)	
Sun et al. (2009)	Stonecrop (*Sedum alfredii*)	
Saraswat and Rai (2009)	Indian mustard (*Brassica juncea*)	
Schröder et al. (2009)	Broadleaf cattail (*Typha latifolia*) and Common reed (*Phragmites australis*)	Extensive root and rhizome systems/active detoxifying enzymes/accessibility of conjugation allies, e.g., γGSH-X, where X=Gly, Gly-NH_2, Gly-OEt, Ala, Glu, Ser

soil augments the translocation of heavy metals from soil into the shoots has opened a wide range of promises (Blaylock et al. 1997). There are two different strategies of phytoextraction have been recognized: (1) hyperaccumulators mediated continuous phytoextraction and (2) chelate supported phytoextraction (Salt et al. 1998). The first strategy is based on the usual ability of a number of plants to accumulate, translocate, and defy elevated amounts of metals over the entire growth succession. The Brassicaceae family which includes 338 genera and more than 3700 species, to which many hyperaccumulator species belong, is also fascinating because the high content of thiocyanates (SCN) makes this species not grazed by animals and diminishes the probability of bioaccumulation of metals in the soil-*plant-animal* continuum during phytoextraction programs. This likelihood of contaminating the food sequence is one of the main hassles linked with phytoextraction techniques. Chelate mediated phytoextraction is based on the fact that the application of multidentate ligands to the soil notably enhances metal accumulation by plants. On the contrary there are cases of low bioavailability of certain metals remaining in soil solid phase which prevents remediation process as well. As a matter of fact, the application of synthetic chelates to the soil must be done vigilantly because of their probable toxicity.

Apart from phytoextraction, phytostabilization is a simple, cost efficient plant-based approach involving the use of plants capable of high tolerance of metals in neighboring soils with small accumulation and low potential environment impact. It focuses mainly on sequestering metals in rhizospheric soil (Jadia and Fulekar 2009) and limits the mobility and bioavailability of metals in soil either by converting to less deadly forms or release for more fast natural transformation. In a few cases, hydraulic control to avert leachate movement can be accomplished because of the huge extent of water transpired by plants. Chemical immobilization of metals by revegetation plan can be achieved by lessening wind-blown dust, curtailing soil erosion, and reducing contaminant bioavailability to the food chain. Incorporating soil amendments such as organic matter, phosphates, alkalizing agents, and biosolids can decrease solubility of metals in soil and reduce fortification of groundwater as an provisional and timely strategy until other remediation techniques is developed, or as management at locations where other methods would not be economically viable. Some grasses and plants have demonstrated the potential for phytostabilization which are commercially available (Table 17.2). Although phytoextraction appears to be cost effective and ready to app1y, one should always consider phytostabilization as a suitable technique rather than phytoextraction for Ni and Cd. In Ni phytotoxic soils, a ready immediate remediation is available via making the soil calcareous and adding appropriate amendments to maintain soil fertility and to alter physicochemical and biological properties. Adding chelating agents to induce phytoextraction causes leaching of metals to groundwater, and is extremely expensive. Again in phytovolatilization the contaminant like Cd might be released into the atmosphere which warrants adequate planning (Carbonell et al. 1998).

Rhizofiltration is a type of phytoremediation where contaminated large volumes of water having low metal concentrations (100–500 μgL^{-1}) are removed via absorption, concentration, and precipitation by plant roots minimizing deterioration to the environment. In the beginning, appropriate plants with rapid-growth underground biomass are supplied with contaminated water to familiarize the plants. These plants are then relocated to the contaminated site to collect the metals, and once the roots are saturated, they are harvested for disposal or reutilization. Exudates from root and variation in rhizosphere pH also may cause metals to precipitate onto root surfaces. Terrestrial plants (Table 17.3) are more successful than aquatic plants because of few added structural and functional characteristics with reference to root mass (Dushenkov et al. 1995). In a greenhouse study Dushenkov and Kapulnik (2000) worked out the distinctiveness of the model plant for rhizofiltration. The ideal plants should produce significant amounts of root biomass with ability to accrue and endure significant amounts of the intended metals in combination with effortless handling, low maintenance cost, and a least amount of secondary waste requiring disposal. Aquatic higher plants like water hyacinth (*Eichhornia crassipes*),

Table 17.2 Phytostabilization potential of different crop species

Reference	Plant species	Mechanism
Zhang et al. (2012)	Lady-fern (*Athyrium wardii*)	Retention capacity in roots
Solís-Dominguez et al. (2012)	Buffalo grass (*Bouteloua dactyloides*), mesquite (*Prosopis sp*), and catclaw acacia (*Acacia greggii*)	Reduced tailings toxicity as well as the potential for metal mobilization
Mendez et al. (2007)	Quailbush (*Atriplex lentiformis* (Torr.) S. Wats.)	Accumulation in the shoot tissues
Blaylock et al. (1995)	Poplar (*P. trichocarpa*)	Root biomass immobilize contaminants and hold contaminants in the roots
Vazquez et al. (2006)	White lupin (*Lupinus albus*)	Citrate excretion/accumulation of heavy metals in roots/root nodules
dos Santos et al. (2007)	Signal grass (*Brachiaria decumbens*)	Complexation and precipitation
Alvarenga et al. (2009)	Ryegrass (*Lolium perenne* L.)	With organic amendment metal immobilized and the mobile fraction decreased
Ehsan et al. (2007), Mendez and Maier (2008)	Lupins (*Lupinus uncinatus* Schldl.)	Metal-tolerant, Cd_{Shoot}:Cd_{Root} <1
Cetinkaya and Sozen (2011)	5 tree, 4 shrub, and 23 herbaceous plant species in the mining site of semiarid environment region	

pennywort (*Hydrocotyle umbellata*), duckweed (*Lemna minor*), and water velvet (*Azolla pinnata*) can remove various heavy metals effectively from solution. Among terrestrial plants Indian mustard (*Brassica juncea*), sunflower (*Helianthus annuus*), spinach (*Spinacia oleracea*), corn (*Zea mays*) and tobacco (*Nicotiana tabacum*), and several members of the Brassicaceae and Poaceae family effectively remove metals including Ni and Cd. The vacuole plays a significant task in the storage of Ni and Cd ions which are thought to be chelated by organic acids, such as citrate or malate, or by phytochelatins. Constructed wetlands can be successfully used as a cost-effective treatment for metals-contaminated wastewater. This system can be either in situ or can be placed anywhere.

However, the relevance of this plant-based know-how may be more challenging and susceptible to failure than other methods of similar cost. The production of hydroponically grown transplants and the maintenance of successful hydroponic systems in the field will necessitate the expertise of skilled personnel, and the facilities and specific equipment required can amplify overhead costs. Possibly the greatest advantage of this remediation method is related to optimistic public discernment.

Although phytoremediation technologies which gained attention recently will likely be restricted to use in shallow soils with relatively low levels of (2.5–100 ppm) metal contamination. It is pertinent that some of the applications of

Table 17.3 Rhizofiltration potential of different crop species

Reference	Plant species	Remarks
Terrestrial plants		
Dushenkov et al. (1995)	Sunflower (*Helianthus annuus* L.) and Indian mustard (*Brassica juncea* Czern.)	Incorporation in tissue and root-mediated precipitation
Ali et al. (2004)	Reed (*Phragmites australis*)	Metal bioconcentration (tissue concentration/solution concentration) was higher in roots than in shoots
Prasad and Freitas (2000)	Holly Oak (*Quercus ilex* L.)	
Candelario-Torres et al. (2009)	Tobacco (*N. tabacum*)	
López-Chuken and Young (2010)	Alfalfa (*Medicago sativa*)	
Aquatic plants		
Veselý et al. (2011)	Water lettuce (*Pistia stratiotes* L.)	Sorption in roots
Suñe et al. (2007)	Giant salvinia (*Salvinia herzogii*) and Water cabbage (*Pistia stratiotes*)	Adsorption, chelation, and ionic exchange
Maine et al. (2001)	Floating macrophytes (*Salvinia herzogii*, *Pistia stratiotes*, *Hydromistia stolonifera,* and *Eichhornia crassipes*)	Sorption in roots
Phetsombat et al. (2006)	Aquatic fern (*Salvinia cucullata*)	
Khilji and Bareen (2008)	Hydrophyte (*Hydrocotyle umbellata* L.)	
Kay et al. (1984), Zhou (1999)	Water hyacinth (*Eichhornia crassipes* (Mart.) Solms	
Dierberg et al. (1987)	Pennywort (*Hydrocotyle umbellata* L.)	
Mo et al. (1989)	Duckweed (*Lemna minor* L)	
Sanità di Toppi et al. (2007)	Aquatic macrophytes (*Pistia stratiotes* L. and *Eichhornia crassipes* (Mart.) Solms)	Glutathione levels/phytochelatin synthesis/antioxidant enzymes and ascorbate peroxidase

phytoremediation have shown potential for use at contaminated sites. A range of plants are being investigated for favorable physiological attributes like root architecture and uptake kinetics.

17.3.1.3 Phytoremediation Assisted by Soil Rhizobacteria

Improvement of phytoremediation processes warrants a sound perception of the complex rhizosphere which contains huge microbial inhabitants with high metabolic activity in contrast to bulk soil. The root system of plants network with a sizable number of diverse microorganisms, which in turn decides the efficacy of phytoremediation (Glick 2003, Whiting et al. 2001). The execution of this association in metal contaminated soil can have an effect from the side of the microbes and the host plant equally. Rhizobacteria are acknowledged to influence heavy metals mobility and accessibility to the plant through mechanism like chelation, acidification, solubilization, and redox reaction (Abou-Shanab et al. 2003; Smith et al. 1995) and cooperate noteworthy part in nutrient recycling, production of phytohormones and siderophores, structural stabilization, detoxification, and managing biotic stress pests and plant growth and development (Elsgaard et al. 2001; Filip 2002; Giller et al. 1998; Glick 2003). Apart from this, plants and bacteria can outline definite associations in which the plant provides the bacteria with a carbon source in the form of hexose that persuade the bacteria to lessen the phytotoxicity of the contaminated soil. Otherwise, non-specific associations can be formed between plants and bacteria and usual plant processes possibly through root exudation encourage the microbial community for detoxifying contaminants through normal metabolic activity. Experiments showed that some rhizobacteria (*Variovorax*, *Rhodococcus*, *Flavobacterium*) can exude antibiotics, organic acids, siderophores, 1-aminocyclopropane-1-carboxylic acid (ACC) deaminase which amplify bioavailability and facilitate root absorption of Cd (Belimov et al. 2005), enhance tolerance of host plants by improving the P absorption (Davies et al. 2001; Liu et al. 2009), and encourage plant growth (Ellis et al. 2000; Meyer 2000).

17.3.1.4 Arbuscular Mycorrhizal Fungi

Among the other microorganisms that received much attention for their ability to alleviate heavy metal, mycorrhizal fungi have consistently been demonstrated the role through a series of rhizosphere processes (Aloui et al. 2011). Away from the rhizosphere, AM hyphae act as the extension of roots and may thus extend the rhizosphere into the bulk soil (Barea and Jeffries 1995). AM fungi may perhaps boost phytoremediation, especially phytoextraction and phytostabilization in particular, by a series of changes in plant physiology with reference to distribution and dynamic of the targeted metal. A lot of plants are exceedingly reliant on AM for their growth and they are involved in the transfer of pollutant elements like Ni and Cd from the soil to the plants (Table 17.4). AM fungi can contribute to plant growth, particularly in disturbed ecosystem, by increasing the plant contact to comparatively immobile nutrients, retention by fungal mycelium, fixation by polyphosphate granules, and improving the soil texture and sequestration of potential toxic metals by producing the soil protein glomalin (Pal 2011).

Research conducted at diverse ecologies (Galli et al. 1994; Diaz et al. 1996) on mycorhizoremediation have demonstrated that AM fungi ecotypes from metal contaminated locations appear to be more tolerant to heavy metals than reference strains from control soils and in due course of time they have developed resistance. Furthermore, AM fungi belonging to *Glomus* and *Gigaspora* genera can speed up the revegetation of numerous degraded metal polluted habitats with dominance of Cd and Ni in soil exchange complex (Gaur and Adholeya 2004; Raman et al. 1993; Raman and Sambandan 1998; Chaudhry et al. 1999). The efficiency of various isolates of one species can vary in their effectiveness toward adaptation and tolerance

Table 17.4 Summary of phytoextraction of Ni and Cd by mycorrhization

Heavy metal	AM species	Plant species	Reference
Ni	*Glomus claroideum*	Leek (*Allium porrum*), Sorghum (*Sorghum bicolor*)	Del et al. (1999)
	Glomus tenue, *Gigaspora*	Berkheya (*Berkheya coddii*)	Turnau and Przybylowicz (2003)
	Glomus mosseae	Barley (*Hordeum vulgare*), common vetch (*Vicia sativa*)	Aysen and Karaaarslan (2011)
	Glomus mosseae (BEG 107)	Cucumber (*Cucumis sativus*)	Lee and George (2005)
	Glomus mosseae (Nicol. and Gerd.)	Bean (*Phaseolus vulgaris* L.) and maize (*Zea mays*)	Guo et al. (1996)
	Glomus mosseae	Ryegrass (*Lolium perenne* L.)	Takacs and Voros (2003)
	Glomus mosseae	Soybean (*Glycine max* (L.) Merrill) and lentil (*Lens culinaris* Medic)	Jamal et al. (2002)
	Glomus clarum; Glomus mosseae, and *Glomus fasciculatum*	Faba been (*Vicia faba*)	Abdel-Aziz et al. (1997)
Cd	*Glomus mosseae*	Leek (*Allium porrum*)	Weissenhorn et al. (1993)
	Glomus mosseae, *Gigaspora*	White clover (*Trifolium repens*), Barley (*Hordeum vulgare*)	Vivas et al. (2003), Tullio et al. (2003)
	Glomus claroideum	Maize (*Zea mays*)	Liao et al. (2003)
	Glomus mosseae and Mixed AM innocula	Subterranean clover (*Trifolium subterraneum*)	Joner et al. (2000)
	Glomus mosseae	Common bean (*Phaseolus vulgaris*)	Guo et al. (1996)
	Mixed AM innocula	Water-spinach (*Ipomoea aquatic*)	Bhaduri and Fulekar (2012)
	Glomus microcarpusum, *G. macrocarpum*, *G. massei*, *G. intraradices and G. fasciculatum and Gigaspora margarita and G. heterogama*	Sorghum (*Sorghum bicolor*)	Arora and Sharma (2009)
	Glomus mosseae	Soybean (*Glycine max*)	Heggo et al. (1990)
	Glomus mosseae	Maize (*Zea mays*) and Lettuce (*Lactuca sativa*)	Schtiepp et al. (1987)

to metal contamination (Malcova et al. 2003). In a long term metal contamination experiment in Spain, Del et al. (1999) reported that *Glomus claroideum* isolates showed a potential adjustment with reference to tolerance and adaptation compared to *Glomus mosseae*. Weissenhorn et al. (1994) illustrated the protocol for developing Cd tolerance in AM fungi treated with $CdNO_3$ @ 40 mg Cd kg^{-1} for one year with the proposition that such fast appearance of metal tolerance is based on phenotypic plasticity to a certain extent than on the selection of tolerant genotypes. The mechanism through which mycorrhization protects roots from metal injury by preventing access of metal to sensitive extracellular and intracellular sites, or by excretion or intrinsic water soluble complex metal-chelators, or by other defense systems. It is likely that AM fungi provide protection through glutathione reductase since elevated concentrations of this thiol were found in pure cultures of the fungi than in bare roots. The development of stress-tolerant plant-mycorrhizal associations may be a promising new strategy for phytoremediation and soil amelioration measures.

17.3.1.5 Bioleaching

Bioleaching, originally emanated from mining industry make use of bacterial bioinoculant (*Acidithiobacillus*, *Leptospirillum*, *Bacillus*) instead of chemicals for solubilization of metal contaminants either by direct action of the bacteria, as a consequence of connections with metabolic products, or both under on site or off site conditions for removal of metals from soils. Bioleaching technology is still in the formative stages for metals like Cd and Ni. Using the metabolite produced from gram-positive heterotrophs of *Bacillus* species isolated from the nodules, a novel process have been proposed for Ni. Further Kumari and Natarajan (2001) were successful to mine precious metals from the nodules by electro bioleaching using acid producing chemolithotrophs like *Acidithiobacillus ferrooxidans* and *Acidithiobacillus thiooxidans*. But these processes utilized an extremely acidic environment complemented with thermal or electrical energy for recovering a considerable quantity of metals which open new perceptions for this bio-oxidation process applied as a strategy for heavy metal remediation.

17.3.1.6 Biochemical Processes

Microbial mediated redox reactions are capable of reorienting mobility (Means and Hinchee 1994) which in turn can help remediation process. A number of microorganisms can oxidize or reduce metal contaminants straightway whereas others generate chemical oxidizing/reducing agents that interrelate with the metals to cause a change in oxidation state which manipulates mobility of metal contaminants. Cd has been observed to be oxidized through microbial processes in the presence of fitting natural inhabitant microorganisms (Valls et al. 2000). The studies on the ability of this organism to lower the toxicity of Cd have so far been promising although they produce metallothioneins rarely (Stillman 1995). Microbial mediated methylation involves attaching methyl groups to inorganic forms of metal ions to form volatile organometallic compounds which subsequently removed through volatilization. On the other hand, organometallics are also more lethal and mobile than other metal forms and may potentially contaminate neighboring surface waters and groundwater (Means and Hinchee 1994). Ni has been removed from plating wastes by bacteria and other organisms are being genetically engineered to eliminate metals like Cd. As of now the systematic use of biochemical processes in the design of engineered metal remediation is well documented but a site-specific, cost-benefit analysis is required to determine its feasibility and adaptation.

17.4 Conclusions

From discussion made in the previous section the following questions have been addressed trying to reach to a conclusion regarding (1) what bioremediation methods are available for deliberation? (2) under what conditions should a particular method be considered at a particular site? (3) which method is most fitting? (4) is bioremediation cost efficient? The varied bioremediation technologies guarantees that one or more of them may be appropriate for a remediation scheme. With the present form of understanding of different processes linked to ecology, physiology, evolution, biochemistry, and genetics, there is a continuous trend of transferring from the treatment of effects to the treatment of contaminant sources. Further, biological treatments are more site precise and often involve more acquaintance concerning a site than is required when using other remediation methods. The overall cost-effectiveness of bioremediation and its prospect to eliminate contaminants without causing cross-media contamination indicates a lifelong need for knowledge and research. Again our existing information of alteration in microbial communities throughout a bioremediation process is very incomplete. As a result of which this green technology frequently faces the complications of identifying the root and developing actions in the case of failure from a microbiological point of view. The latest advances in the field of molecular biology appear extremely promising. Interdisciplinary approach involving microbiology, engineering, ecology, earth science, chemistry, social science, and law can effectively resolve the issue in a comprehensive way. Supplementary research is also needed in order to improve the relevance of bioremediation for management of metals-contaminated sites with an in-depth understanding of the mechanisms involved in mobilization and transfer of metals. Despite the different bottlenecks, the upcoming of bioremediation appears bright as the progresses in the different disciples that shape bioremediation are picking up pace and momentum. Indeed it is inevitable that a growing necessity for environmentally friendly smart bioremediation know-how can be seen in the future with a special reference in developing countries.

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Urban Soil's Functions: Monitoring, Assessment, and Management

18

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Abstract

Urbanization is a key trend of current land-use change, responsible for large environmental changes worldwide. Sustainable functioning of urban ecosystems is a priority goal of today and nearest future. Urban soil is a key component of urban ecosystems. Urban soils are formed and exist under predominant direct and indirect effect of anthropogenic factor. Urbanization was traditionally related to negative impacts on soils, whereas the capacity of urban soils to perform environmental functions is poorly understood. Traditional approaches to assess and standardize soil quality through static parameters and health

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thresholds give limited information on soil living phase and its dynamics. Quantifying urban soils' functions directly relates soil quality to the role of soil for environment and society, that is especially relevant in urban ecosystems. This chapter aims to overview existing approaches to monitor and assess soil functions for a specific case of urban soils. Individual functions (i.e., gas exchange and carbon sequestration, bioresources, remediation, etc.) are observed over variety of bioclimatic conditions and for different levels of anthropogenic disturbance. Assessment results are further implemented to develop guidelines and best management practices to construct and treat urban soils for maintaining their functions and quality.

Keywords
Urbanization • Technosols • Soil organic carbon • CO_2 emissions • Heavy metals • Remediation • Soil constructions • Moscow

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18.1 Introduction

Urban ecosystem is a relatively new ecological phenomenon. The first archeological settlements, recognized as towns, date back to 8–10,000 years ago. The first megapolis with the population over one million—the city of Rome—achieved this threshold in the first century BC during the Julius Cesar reign (Denisov et al. 2008). Only 16 cities in the world exceeded one million citizens by 1900. However, this number rapidly increased to more than 400 at the beginning of the twenty-first century (Berry 2008). Urban ecosystems are the most artificial compared to agricultural and natural systems. They are driven by humans and for humans and anthropogenic factors have a predominant influence on such urban environments.

Although urbanization is the most rapid current land-use change trend, urban soil's quality and functions still lack attention. Historically urban soils were ignored by major soil surveys and major conventional soil classifications didn't pay attention to urban soils. Intensive anthropogenic load on soils highlighted attention to soil's health and sanitary quality. Urban soils then were presented as possessing low fertility and exposed to severe disturbances. The most recent concepts of "sustainable cities" focus on urban soil's potential to provide functions and support services, important for humans and environment. Currently, urban soils face a paradox of being of the highest value regarding property and building issue, and being almost totally ignored with regard to the functions and ecosystem services they can provide (Morel et al. 2014). The potential of urban soils to play a key role in an ecosystem of a sustainable city is still poorly studied and rarely used.

In this chapter we aggregated existing knowledge on practices in monitoring, assessing, and managing urban soil's functions. Specific conditions of urban soil's formation and functioning are discussed in Sect. 18.2. Different approaches to identify and classify urban soils and the provided functions are presented in context of highly heterogeneous urban environment (Sect. 18.2.2). Alternative views on urban soil's quality and possibilities to assess it based on urban soil's functions are given in Sect. 18.2.3. The methodology to monitor and assess urban soil's functions is reviewed in Sect. 18.3.1. Different parameters and approaches including resources' assessment, monitoring gas exchange and carbon sequestration, and analyzing soil microbiological activity are discussed. Sections 18.3.2–18.3.4 present assessments of urban soils' functions in different bioclimatic conditions and scales, including monitoring and assessment of urban soils' regimes in Moscow, environmental and economical assessment of soil functions in the Moscow Region. Finally, possible implementations of the assessment results for urban soils' management are discussed in Sect. 18.4, ranging from the straightforward guidelines to manage contaminated soils (Sect. 18.4.2) to more advances automatic intellectual systems and models to optimize urban soil construction (Sects. 18.4.3–18.4.4).

18.2 Soils and Their Functions in Urban Ecosystems

18.2.1 An Overview of Soil Functions' Concept

Soil is a key ecosystems component, playing an important role for environment and human wellbeing (Dobrovolskii and Nikitin 1990; Dobrovolskii and Nikitin 2012; Kazeev et al. 2003; Blum 2005). Soil is vulnerable to environmental risks and threats, such as erosion, decline in fertility and biodiversity, sealing, contamination, and compaction. Monitoring and assessing soil quality at the multiple scales and for different land-uses is among the most essential directions in applied soil science and ecology. Several approaches to distinguish and assess soil quality are known. Historical attitude to soil as an agricultural resource related soil quality to the parameters of soil fertility: organic matter and nutrient content, soil acidity, and texture (Ali 2003; Mairura et al. 2007). Assessment of these agricultural parameters and integral agricultural indexes considered harvested biomass as the primary indicator of soil quality (Karmanov et al. 2002; Bastida et al. 2008). Intensive industrialization and urbanization of the last century resulted in increased anthropogenic pressures on soil, including chemical and biological contamination (Abrahams 2002; Kurbatova et al. 2004). Arisen risk for human health from interaction with contaminated soils highlighted importance of sanitary-hygienic soil quality, assessed through comparison of soil contaminants' concentrations to different standards and health thresholds (CP-11-102-97 1997, MD-2.1.7.730-99 1999). Global environmental problems, including climate change, desertification, soil degrading, and biodiversity depletion, emerged in scientific and political agendas last decades (IPCC 2001; Kazeev et al. 2003) shifted tradition attitude to soil quality towards its role in global biogeochemical processes and provisioning services, like carbon sequestration or genetic reservoir (Swift 2011; Janzen 2004; Blum 2005). Soil quality therefore was related to its functions, rather than to individual features (Karlen et al. 1997).

The term «soil function» or more precisely «soil ecological (environmental) function» was introduced to research and political debates in 1970s to highlight soil's contribution to environment and biosphere (Kovda 1973, 1975, 1981). Primarily distinguished soil functions were rather general and referred mainly to the global scale (i.e., «support for life on the Earth» or «linkage between biological and geological cycles») (Kovda and Rozanov 1988). Impetuous increase of researches in this sphere in the beginning of the twenty-first century resulted in more concrete definitions and more detailed classifications.

Two alternative approaches to define soil functions were developed in Russia (USSR) and US and EU countries. In Russia soil function was defined as a role of soil and soil processes in ecosystems, their preservation and evolution (Dobrovolskii and Nikitin 2012). In contrast, more practical and human-oriented understanding of soil function as an impact of soil processes on the environment and human wellbeing is widely accepted in EU and US research communities (Nortcliff 2002). The purposes of soil functions' implementation also differ between the countries and research schools. For example, analyzing soil functions in land evaluation and land-use planning is among the most essential soil science practices in Germany, UK, and USA (Karlen et al. 2001; Vrscaj et al. 2008), whereas in Russia and post-soviet countries soil functions' concept is more likely used for the purposes of nature conservation, including developing the Red Book of Russian soils (Dobrovolskii et al. 2001; Aparin 2007; Dobrovolskii and Nikitin 2009).

Obtained differences in Russian and international approaches get more evident when analyzing soil functions' classifications. Russian classification includes global and biogeocoenotic functions (Dobrovolskii and Nikitin 2012) and focuses on the multiple-scale interactions between soil and environment. Different European and American classifications propose functions, usually subdivided to ecological and non-ecological (Blum 2005) or natural and useful for man (BBodSchG 1998) with especial attention to soil–human interaction. Different classifications are usually in good coherence regarding the main distinguished functions, however, some divergence occurs (Table 18.1).

Although classification and diagnostics of soil functions was thoroughly studied, much less is known on the methodologies and parameters to quantify soil functions, which constrains implementing the concept in practice (Brown 2003; Vrscaj et al. 2008; Vasenev et al. 2012). Results of soil functions' monitoring and assessment available from literature usually consider a limited number of individual functions, rather than an integral assessment of soil functioning (Kaye et al. 2005; Ananyeva et al. 2008; Smagin 2012). Major assessments of soil functions are focused on natural and agricultural areas, whereas urban ecosystems remain under-observed (Kurbatova et al. 2004; Bond-Lamberty and Thomson 2010; Vasenev et al. 2014a). This chapter aims to review existing approaches to monitor and assess urban soils' function and to illustrate their implementation for environmental assessment, standardization, and soil management practices.

18.2.2 Urban Soils: Formation and Classification

Urban soils are traditionally assumed as exposed to intensive anthropogenic disturbance through sealing, over compaction, pollution, and salinization (Burghardt 1994; Stroganova et al. 1998; Craul 1992). However, this direct anthropogenic influence on urban soils is further complicated by indirect influences of urban environment, altering soil forming factors and soil functioning (Prokofieva and Stroganova 2004; Pickett et al. 2011; Vasenev et al. 2013a). Urbanization processes result in irreversible alternations in former natural and agricultural landscapes. Resulted urban ecosystems are very different from natural analogues in terms of matter and energy fluxes, vegetation, and soils.

Urban microclimate is very different from one in suburban and natural areas. Smoke and dustiness of urban air decrease total amount of solar radiation and the duration of sun shining period, whereas fogs and cloudiness get more likely. Increased annual precipitation is typical for urban climate. For example, annual precipitation in Moscow city is 25% above the regional standard. Mean air temperature in densely urbanized areas is likely higher and spring/autumn frosts are shorter

Table 18.1 Selected soil functions in different classifications[a]

Blum (2005)	Nortcliff (2002)	Ritz et al. (2009)	BBodSchG (1998)	Andrews et al. (2004)	Dobrovolskii and Nikitin (2012)
Biomass production Participating in biogeochemical cycles, including gas exchange between soil and atmosphere Source of raw materials	Provision of physical, chemical, and biological settings for living organisms Supporting biological activity and diversity for plant growth Filtering, buffering, degrading organic and inorganic substances	Food and fiber production Environmental interactions, including carbon retention Supporting habitats and biodiversity	Participation in water and nutrient cycles Decomposition Basis for life of people, plants, animals, and soil organisms Land for agriculture and silviculture An archive of natural and cultural history	Nutrient cycling Biodiversity and habitat Resistance and resilience	Influence on the gas content Storage of nutrients Habitat for terrestrial organisms Source for minerals' and fossils' formation Transformation and transfer of sun energy to the earth bowels Storage of historical artifacts

[a]We used the original names of the functions, given by the authors of each classification

compared to natural conditions. This effect, often thoroughly described in literature since 19th as the "urban heat island" was shown for some megalopolises and even for small settlements. "Urban heat island" affects the air temperature of the 100–300 m layers above the surface and the temperature increase can surpass several degrees (Landsberg 1981; Oke 1973, 1987). Alteration in air and soil temperature influences urban vegetation, providing better conditions for heat-loving species.

Urban vegetation includes both native and introduces species. The latter ones are more sustainable to urban conditions and therefore spread through substantial extents in settlements with different bioclimatic conditions. Urban lawns can occupy up to 40% of the non-sealed urban areas and are more influenced by urban management than by climatic conditions (Milesi and Running 2005; Vasenev et al. 2014a). It results in biotic homogenizing of urban areas located in different climatic zones and adds to the "intrazonal" features of urban landscapes (Müller et al. 2013). Ornamental trees and shrubs, lawns, and flower-beds require specific soil conditions and therefore receive specific soil management like fertilization and irrigation (Vasenev et al. 2015).

Relief and parent materials are another soil forming factors, exposed to irreversible alteration in urban conditions. Urban relief is predominantly artificial. Most of the natural hollows and gullies are filled in and hills are leveled to provide the basis for building construction, landscape, and architectural development. These transformations alter surface run-off and affect soil water balance. The changes in run-off and infiltration may lead to temporally saturation of the urban soils (Kurbatova et al. 2004; Pickett et al. 2011). Parent materials for urban soils' formation include natural and technogenic sediments, cultural layers, and even buried horizons of natural soils (Osipov and Medvedev 1997). These parent materials have a very diverse chemical composition including toxic substances, sewage, industrial and domestic wastes (Prokof'eva et al. 2007). Dust deposition is another important factor, influencing parent materials of urban soils and contributing to the vertical growth of the sediments layers. Urban dust includes soil, rock, and technogenic particles. The role of each component is determined by natural lithological conditions and local sources of air pollution (Miyamoto et al. 2003; Plyaskina 2007; Da Costa Duarte and Oliveira Duarte 2009). Chemical composition of the urban dust depends on the anthropogenic pressure and dominating industries (Yazikov et al. 2004). Dust deposition affects urban soils' features through, for example, increasing carbon, calcium, magnesium, sulfur, chlorine, and heavy metals content (Plyaskina 2007; Prokof'eva et al. 2015). After deposition, dust particles mix with urban topsoil by mesofauna and are affected by soil fungi.

Temporal dynamic of urban soils is also very specific. Permanent anthropogenic disturbances of urban relief and formation of anthropogenic sediments result in short cycles of soils' formation and "young" age of urban soils. Moreover, different susceptibility of urban soil layers to anthropogenic disturbances result in different ages of urban soils' horizons. Dust sedimentation and greenery contributes to the vertical growth of soil layers. This trend of topsoil' vertical growing is referred as "synlithogenic" trend in soil forming process. Synlithogenic soil formation is typical for urban soils and, in contrast, is rare for natural soils, where the major soil forming processes usually are directed down the profile (except, for alluvial and volcanic soils) (Dobrovolsky and Urussevskaya 2004). In result, the relative age of urban topsoil is always younger than in subsoil layers.

Indirect anthropogenic influence results in the following typical; features of urban soil formation: (1) vertical growth of topsoil layers and predominantly “synlithogenic” soil formation process; (2) short time periods for soil formation, resulting in the primitive stages of pedogenesis, typical for some (mainly topsoil) horizons; (3) specific chemical features, caused by dust deposition and anthropogenic disturbances and including alkaline pH, contamination with heavy matters and hydrocarbons, increased carbon and phosphorous content; (4) altered physical features, including high bulk density and stoniness; and (5) specific biological community both in terms of biodiversity and total biomass.

Specific factors of urban soil formation and their specific features determine substantial differences between urban and non-urban soils, recognized by regional and international classifications, which distinguish urban soils as an individual taxon. The international soil classification World Reference Base (WRB) for soil resource distinguishes two reference groups for soil exposed to anthropogenic transformation: (1) Anthrosols for the soils, formed by agricultural activity and (2) Technosols for the soils, formed at the primary soil formation stages with a geomembrane or technic hard material and containing significant amount of artifacts (Rossiter 2007). Most of the soil observed in urban areas relate to the Technosols reference group. Urban soil can also be defined by a qualifier “Technic” if the amount of included artifacts is below required 20% to relate it to Technosols. The latest edition of WRB also includes the “Pretic” qualifier for urban soils, formed on the ancient cultural layers, containing increased amount of phosphorous and carbon and few solid inclusions.

The approach to identify urban soils, implemented in WRB, similarly to approaches used in several regional classification systems (Burghardt 2000; Prokofyeva et al. 2011; Prokof’eva et al. 2013) focus on the young age, synlithogenic features of soil formation, and specific features, for example, neutral or slightly alkaline pH, high bulk density and increased concentration of contaminants, plentiful anthropogenic inclusion, and artifacts. Urban soils’ diagnostic is based on the specific diagnostic horizons (i.e., urbic horizon (UR), resulting from long-term urban pedogenesis and forming in parallel with the synlithogenic deposition of parent material; rehabilitation horizon (RAT), including organic substrates of different origin (peat, composts, fertilizers) implemented to rehabilitate damaged lands or reclaim poor mineral substrates; “technogenic” horizon (TCH), including technogenic deposits of different composition and origin). Different urban soils’ groups distinguished by regional classifications can be more detailed than those proposed by WRB. For example, the classification of urban soils proposed for Moscow city include such types and sub-types as “urbanozems,” “replantozems”, “culturozems,” “urbochemozems,” “necrozems,” “constructozems,” and others (Stroganova et al. 1998; Prokof’eva et al. 2014).

18.2.3 Analyzing Soil Functions to Assess Soil Quality

Spatial heterogeneity and complexity of urban soils in terms of their profiles, morphological, chemical and biological features constrains their ecological standardization and makes assessing urban soils' quality challenging. Different approaches to assess and standardize urban soil's quality exist. The most basic methods compare selected soil features to agrochemical standards or health thresholds. The more advanced approaches consider urban soils' functions and provided ecosystem services as the basis for soil quality assessment. The assessments of soil agrochemical quality vary from measuring conventional soil features (i.e., soil organic carbon, pH, nutrients' contents) (quality (Ali 2003; Barrios and Trejo 2003; Mairura et al. 2007) to more advanced integral indexes (i.e., soil ecological index and agroecological index) (Vasenev and Bukreyev 1994; Karmanov et al. 2002; Savich et al. 2003). Intensive industrialization of the twentieth century and resulted technogenic pressures on soils highlighted sanitary indicators of soil quality, based on comparison of soil pollutants' concentrations to the corresponding health thresholds (i.e., maximal permissible concentration (MPC), estimated permissible concentration (EPC), and an integral Zc index) (HS-2.1.7.2041.06 2006; CP-11-102-97 1997). Chemical soil features as soil quality indicators are sometimes criticized for poor correspondence with soil living phase. Soil biological parameters recently got widely accepted, since they strongly link to majority of soil processes and functions and are very sensitive to anthropogenic pressures (Nortcliff 2002; Gil-Sotres et al. 2005; Gavrilenko et al. 2011; Vasenev et al. 2012; Creamer et al. 2014). The outcomes can, for example, include changes in abundance and species composition of soil microorganisms and their activity resulting from increased anthropogenic disturbance (Kolesnokov et al. 2001; Kazeev et al. 2003; Yakovlev and Evdokimova 2011). Biological indicators of soil quality vary from rather simple and straightforward such as microbial biomass carbon (Wardle 1992; Nannipieri et al. 2002; Ananyeva et al. 2008) or microbial respiration (Ananyeva 2003; Castaldi et al. 2004; Vasenev et al. 2012) to more complex indicators of genetic profiles (Ritz et al. 2009).

Soil quality is usually defined as soil's capacity to perform functions (Karlen et al. 1997; Makarov 2003). Analyzing soil functions is widely used to assess soil quality. Parameters of soil functions used to assess soil quality differ by origin (chemical, physical, and biological) (Nortcliff 2002) and by information source (experimental and calculated) (Bastida et al. 2008). Although the parameters are different, most of them shall satisfy the following requirements as reviewed by Doran (2002): (1) direct relation to corresponding soil functions, (2) reflection of the principal soil processes, (3) sensitivity to land-use change, (4) clarity for stakeholders, and (5) cost and labor accessibility. Soils perform different functions simultaneously (Blum 2005). The consequences of anthropogenic influences on different soil functions can also be different. At the same time, an integral assessment combining the individual soil functions is needed for practical application (Brown 2003). The results of integral assessments and assessment of the individual soil functions complement each other but are not interchangeable. Considering variability of soil features and processes, soil functions measured for different land-use types and bioclimatic conditions shall be standardized (Nortcliff 2002). Relating observed soil functions to those of natural ecosystems in the climax state is a widely used standardization approach (Fedoroff 1987; Gil-Sotres et al. 2005). For this purpose, reference natural ecosystems in similar climatic and lithological conditions to investigated ones are identified. Assessments of urban soils' quality based on the performed soil functions are still rare, compared to soils in natural and agricultural areas. This chapter aims to review different approaches to monitor, analyze, and access urban soils' function as a background for sustainable management of urban soils.

18.3 Approaching to Assess and Monitor Urban soil's Functions

18.3.1 Methodology to Assess Urban Soils' Quality and Functions

18.3.1.1 A Resource-Based Approach for Assessing Urban Soils Quality

The major methodologies conventionally used for ecological evaluation of soil have been derived from a research of homogeneous contiguous environments: water and air. The quality of these environments may be objectively assessed by a value of one of the indicators, which can be used to represent the entire object. Soils, within systems of genetic and functional horizons, and lateral spatial variability, require a different methodology. This methodology should include traditional indicators as well as concentrations of certain substances from given locations with integral characteristics. These integral characteristics reflect *stocks of matter* in the entire soil profile per unit area. We propose that such an approach for soil quality evaluation be referred to as a resource approach. This approach describes a specific amount of soil on a specific area and the amount of deposited substances therein. The latter is divided into beneficial substances (nutrients for plants and soil organisms, and structural components) and harmful substances (pollutants and their complexes) (Smagin et al. 2008). These stocks constitute a real soil resource that can be accurately measured (t/ha, kg/m^2), and be accounted and monitored. They can also be reproduced and remediated (removing a certain amount of harmful substances from a defined area). Soil resources can be evaluated economically at a market value of an adequate weight (volume) of clean fertile soil in a normative layer on a specific land area.

Estimating stocks instead of conventional concentrations enables for a more accurate identification of contaminated urban areas as it was reported by Smagin et al. (2008) for Moscow. Implementing the resource-based approach the authors showed that in the center of the city more than half of the studied soils have exceeded thresholds for the main pollutants. Moreover, most of them have exceeded MPC (EPC) not only in topsoil but also in subsurface horizons over 1 m depth. A similar approach for an environmental regulation of urban soils has been applied for conditionally beneficial substances. These substances are based on essential major nutrients (C, N, P, K) that influence soil fertility and plant growth (Smagin et al. 2008).

18.3.1.2 Measuring Gas Exchange and Carbon Sequestration in Urban Soils

Soil plays a key role in the carbon balance and makes a major contribution to carbon stocks and fluxes (Raich et al. 2002; Schulze 2006). Carbon sequestration and gas exchange are recognized as important soil functions (Swift 2011; Lal 2004). Although different approaches to classify and identify soil functions exist as it was shown in Sect. 18.2.1, they all consider carbon stocks and fluxes as important parameters: up to two thirds of the soil functions are directly or indirectly related to soil carbon cycle. The recently emerged concept of ecosystem services (ESs; MA 2003) expands analyzing environmental properties, processes, and functions with human economic benefits (de Groot 1992; Costanza et al. 1997). Although, soil services are considered part of ESs (Breure et al. 2012), soil carbon sequestration and emissions directly or indirectly affect many specific ESs, including soil fertility maintenance, food production, and climate regulation (MA 2003; TEEB 2010). Methodologies to analyze carbons stocks and soil respiration include field and laboratory approaches, both adopted for the specific urban environment.

Field part of soil carbons stocks' assessments includes investigation of soil profiles and sampling from different horizons or depth layers with further analysis in the laboratory conditions. Soil sampling in urban areas is constrained by their specific spatial structure, complicated with functional and historical zoning and soil sealing (Vasenev et al. 2015). For example, soil sealing is among the main direct anthropogenic influences on urban soils. Sealed soils defined as Ekranic Technosols in WRB (Rossiter 2007) are very challenging to analyze, since sampling these soils is very labor consuming and difficult to get approval for. Sampling from the non-sealed urban areas is usually performed by augering with further reconstruction of the profile and collecting samples from different depths. The depth of augering shall consider the subsoil carbons stocks including ones in the "cultural layers" (Dolgikh and Aleksandrovskii 2010; Vasenev et al. 2013b) and at least 100–150 cm is a recommended.

Field methods to analyze soil respiration (Rs) are based on direct in situ measurements, including alkali absorption techniques (Buyanovsky et al. 1986) and a variety of chamber approaches (open-path, closed-path, and dynamic close chambers) (Nakadai et al. 1993; Bekku et al. 1997; Savage and Davidson 2003). The most advanced current approaches use infra-red gas analyzers (IRGA), providing measurements of CO_2 concentrations with a frequency up to 1 Hz or even higher and thus giving an accurate picture of the CO_2 flux. In addition to measuring total carbon fluxes methods are available to distinguish between SOM-derived and root-derived respiration. The most frequently used methods are based on isotopic approaches (Taneva and Gonzalez-Meler 2011), trenching (Bond-Lambert et al. 2011), and field segregation (Leake et al. 2004; Gavrichkova 2010) as it was reviewed by Hanson et al. (2000). Carbon fluxes' measurements are usually taken in parallel to monitoring soil temperature and soil moisture as the key abiotic drivers of soil respiration (Vasenev et al. 2015).

Samples collected in field are prepared for laboratory analysis, including air-drying, sieving, and pulverizing using a mortar (Vorobyova 1998). Some stages are excluded when soil samples for microbiological analysis are prepared (Creamer et al. 2014). Possible set of the laboratory techniques to analyze urban soil's carbon includes general approaches to quantify total carbon content as well as more detailed measurements of the different fractions: organic, water soluble, hot-water, readily oxidizable, and microbial biomass carbon. In comparison to direct field measurements, soil respiration in laboratory conditions is measured indirectly. Indirect methods estimate soil carbon fluxes as a function of proxy variables obtained from, e.g., remote sensing (Guo et al. 2011; Huang et al. 2013) or measurements of soil microbiological activity under standardized conditions. For example, the basal respiration is a relatively easily measured proxy variable, referring to soil microbiological activity measured in standardized conditions. Basal respiration and in situ respiration methods reflect different processes and obtain therefore characterize soil respiration differently. In situ Rs is sensitive to soil temperature and water regimes and especially to physical disturbance, which is a very common condition in urban areas. It better determines an actual CO_2 efflux and temporal variability in Rs. Basal respiration is strongly linked to chemical soil conditions, influencing the soil microbial community (C and N content, pH, contamination, etc.) and thus characterizes the potential CO_2 emission.

18.3.1.3 Analyzing Soil Microbiological Activity to Quantify Urban Soil's Bioresources

The microbial community is an important soil constituent; its characteristics are recommended for inclusion into the assessments of soil quality and functions (Winding et al. 2005; Bastida et al. 2008). The assessment of soil quality should take into account data on the microbial biomass of soils, the rates of soil respiration, and the rates of nitrogen mineralization. The microbial biomass content (microbial biomass carbon) is one of the most commonly used indicators for soil quality assessments in many studies (Trasar-Cepeda et al. 1998; Kang et al. 2005; Erkossa et al. 2007; Zornova et al. 2007). The microbial biomass is an active agent of the plant residues' decomposition and the destruction of xenobiotic substances in soils. It participates in the cycles of important biogenic elements (C, N, P, S) and in the immobilization of heavy metals and contributes to the stabilization of soil structure (Nannipieri et al. 2002). Though the soil microbial biomass carbon constitutes just several percents of the total soil organic carbon content, it can be considered "the eye of the needle through which all organic material that enters the soil must pass" (Jenkinson 1977). According to researchers the soil microbial biomass is a more sensitive to various disturbances than soil organic carbon content (Anderson and Gray 1989; Wardle 1992; Powlson 1994). Soil microbial biomass carbon content is one of the sensitive indicators of environmental changes (Anderson and Domsch

1986, 1989; Jordan et al. 1995; Hargreaves et al. 2003), therefore it is a valuable index for many ecological researches and monitoring programs (Bölter et al. 2002; Winding et al. 2005). The content of soil microbial biomass may be useful to determine critical thresholds for normal (equilibrium) soil functioning (Knoepp et al. 2000; Andrews and Carroll 2001) to monitor soil quality in various regions and on different scales (Karlen et al. 2001; Arshad and Martin 2002). The microbial biomass carbon is a widely used parameter for soil quality assessment (DIN ISO 14240-1 1997).

Respiratory activity of soil microbial community is also widely used as an indicator of soil resistance to external impacts (Bezdicek et al. 1996; Seybold et al. 1999). Soil (microbial) respiration rate is determined by soil CO_2 production or O_2 consumption (ISO 2002a, b). Soil microbial respiration (soil CO_2 production) is a very sensitive index. Soil microbial respiration is influenced by the soil temperature and moisture, soil structure and nutrients content that predetermines its strong variability in field conditions (Pankhurst et al. 1995). Alternatively, the measurement of soil microbial respiration can be carried out in the laboratory (controlled) conditions, which also excludes contribution to the process of plant roots.

There is lack of data on soil microbiological properties in comparative gradient from natural to urban ecosystems at landscape and regional levels (Lorenz and Kandeler 2005, 2006; Vasenev et al. 2012; Zhao et al. 2013). Soil microbial biomass content, respiration, and microbial community structure are often investigated only for the topsoil (≤20 cm) and at a limited amount of sites, mainly, urban parks and green zones (Li et al. 2001; Matei et al. 2006; Papa et al. 2010; Shirokikh et al. 2011), that is not quite representatively in a variety of anthropogenic impact of urban ecosystem.

The information about microbial community functioning of urban ecosystem is rather scarce. Soil microbial biomass and functions (respiration, consumption of organic substrates) in urban soils were thoroughly described, e.g., for the cities of Aberdeen in Scotland (Yuangen et al. 2006), Caserta in Italy (Papa et al. 2010), Beijing in China (Zhao et al. 2013), Kill and Stuttgart in Germany (Beyer et al. 1995; Lorenz and Kandeler 2005). Low enzymatic and antibiotic activity was shown in soils of some Russian cities (Sharkova et al. 2011; Shirokikh et al. 2011; Gorbov and Bezuglova 2013; Shumilova and Kuimova 2013). Remarkable increase (almost triple) of bacterial nano-forms was reported for the urban soils in Moscow compared to natural analogues. Some local studies report urban soil respiration as comparative or higher than in natural soils (Jo and McPherson 1995; Bandaranayake et al. 2003; Vasenev et al. 2012), although opposite evidences are also known (Castaldi et al. 2004; Barajas-Aceves 2005; Nwachukwu and Pulford 2011). Thus, the basic parameters of many international monitoring programs and assessment of soil quality, including urban soils, focus on microbial biomass and microbial respiration rate (Zavarzin 1994; Höper and Kleefisch 2001; Dilly 2001; Bailey et al. 2002; Schouten et al. 2000; Bloem and Breure 2003).

18.3.2 Monitoring and Assessment of Urban Soil's Functioning Regimes in Moscow Megapolis

Most of research on environmental assessment and standardizing of urban soils focus on the soil features related to solid soil components (i.e., texture, mineralogical, and chemical compounds, including contaminants). However, the resource assessment only focused on the stable parameters may not be enough to assess the quality of soil as a very dynamic substrate. Abundant nutrient content and contaminant's concentration below health thresholds do not guarantee optimal performance of the principal soil functions, including remediation, air quality control, and biomass production. These functions are substantially affected by soil regimes, related to dynamic (non-solid) gas and aqueous phases, physical fields and living organisms. Air and water interactions in soil pores, salt concentrations in soil solutions, soil temperature, and moisture have a predominant effect on soil functioning. Standardizing and monitoring soil regimes for the purposes of urban soils' management have the similar relevance to the more conventional soil resource assessment.

18.3.2.1 Automated Monitoring of the Hydrothermic Features

Monitoring traditional hydrothermic features of urban ecosystems (i.e., temperature and air humidity) is usually based on programmed electronic probes DS1921–DS1923 (USA) (Smagin et al. 2006, 2008). These probes allow for measuring meteorological parameters with high accuracy, frequency, and cost efficiency. In comparison to conventional monitoring techniques, requiring for periodical checking and fitting by the operator, the programmed probes enable a fully autonomous monitoring. Soil temperature regime and its effect on urban vegetation can be assessed based on the following gradation scale developed for the Moscow megapolis (Table 18.2). A good example can be given by temperature regimes' monitoring results obtained for the Kurkino district in Moscow (Fig. 18.1). Soil temperature

Table 18.2 Temperature regimes standard for soils and soil constructions (Smagin et al. 2006)

<−2 °C very low soil temperature	The soil is frozen, the biological activity is suppressed, possible death of root systems and soil organisms
–2 to 0 °C low temperature	The soil is frozen or unfrozen moisture possess a high osmotic pressure, poor biological activity of microorganisms, plants suspended animation
0–5 °C cold soil	Thaw, thawing of the soil, germination of seeds and bulbs, activation of micro-flora
5–10 °C moderately cold soil	Warming up of the soil, heat-loving crops germination, activation of soil fauna
10–15 °C moderately warm soil	Optimal heat supply of the soil, moderate biological activity and crop growth
15–20 °C warm soil	Increased heat supply; activation of evaporation and desiccation of the soil, biological activity and growth is driven by soils moisture
>20 °C high soil temperature	Superfluous heat, drought, and possible inhibition of the biological activity of transpiration and photosynthesis

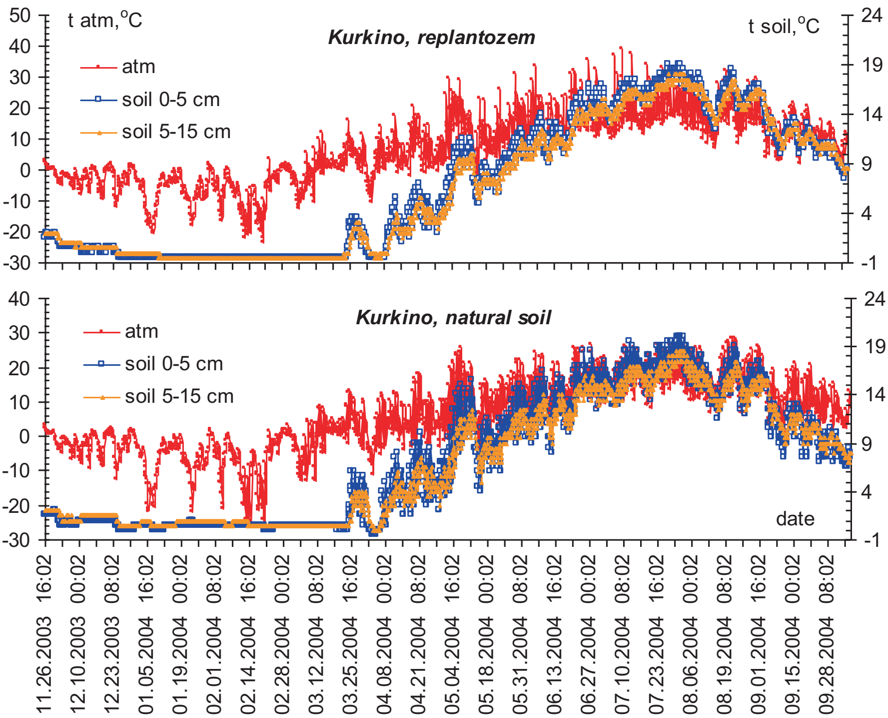


Fig. 18.1 Monitoring results of the urban soils' thermal regime in the residential area of Kurkino district, Moscow

was much more stable than the air temperature during the cold period. Air temperature ranged from values below zero during the thaws to heavy frosts of −20 to 25 °C, whereas soil temperature remained 0–0.5 °C. Different dynamic in soil temperatures was shown for the observed functional zones. Topsoil (5 cm) temperature has never dropped below zero in the recreational zone, dominated by natural soils. Positive temperatures 0.5–1 °C were obtained for the subsoil layers (10–20 cm) in the recreational zone. In contrast, negative −0.5 °C temperatures were obtained for topsoil and subsoil layers starting from late December and early January correspondingly for the disturbed urban soils ("Replantozems"). The negative temperatures for both layers remained till the beginning of April and were not affected by thaws. Lower temperatures in urban soils compared non-disturbed soil is likely resulted from alterations in soil texture and thin (and sometimes lacking) snow cover in urban areas. Long soil frozen periods have a negative influence on urban vegetation, including flowerbeds and green lawns with surface root systems.

18.3.2.2 Monitoring Air-Water Regimes in Urban Soils

Analyzing air-water regime is critical to monitor urban soils' functions, including supporting urban vegetation, gas emission, biodegradation, and hydrological functions. Soil water scarcity during the draught period or lack of air in pores of

Table 18.3 Standards to quantify air-water regime of urban soils based on W/Ws index (Smagin et al. 2006)

Sands	Loamy sands and peat	Sandy loams, loams	Heavy loams, clays	Comments
>0.8–0.9	>0.85–0.9	>0.85–0.9	>0.85–0.9	High non-productive losses (infiltration, evaporation) grow depression by the lack of air in the soil (over-wetting)
0.2–0.85	0.4–0.85	0.5–0.85	0.6–0.85	Optimal for the plants, but non-productive losses (infiltration, evaporation) of water remain high
0.05–0.3	0.15–0.4	0.3–0.5	0.4–0.6	Available for plants water and low non-productive losses (infiltration, evaporation)
<0.05	<0.15	<0.3	<0.4	Non-available for plants water in the soil

water-logged soil can result in plant's death. Nutrient content and pollution do not have any considerable effect for these extreme conditions. Soil water saturation degree (W/Ws) is a relevant indicator to quantify air-water regime in urban soils. This index is estimated as the ratio of water-containing soil pores to the total soil porosity (water holding capacity) (Smagin et al. 2006; Smagin 2012). The index ranges from 0 to 1 with 0 referring to water scarcity and 1 showing absence of air in soil pores. For the environmental standardization purposes this monitoring index was scaled, regarding dispersity (soil texture) and corresponding water holding capacity of different soils and substrates used for soil construction (Smagin et al. 2006; Smagin 2012) (Table 18.3). The proposed scale is based on the fundamental laws of soil physical state and experiments on thermodynamic assessments of soil water holding capacity (Smagin 2003). The index W/Ws is measured by inductive hydrometers or dielcometers or TDR-reflectors (Decagon, Eijkelkamp equipment). More conventional field gravimetric approaches, based on weighting soil sample of known size, are also relevant (Smagin et al. 2006). The approach was tested for the soils of the Moscow Zoo during the 2 years of observation (Fig. 18.2).

Optimal air-water regime in the root layer was obtained for the major part of the vegetation season 2006. Limited water shortage was found in 10% of observation, whereas 24% of the cases showed over-wetting. The next 2007 year was drier and therefore different trends in air-water regime were monitored: optimal conditions, water scarcity, and over-wetting were obtained in 55%, 38%, and 7% of observations, respectively (Fig. 18.2). Seasonal decrease of soil moisture and water content during the dry period is very typical for urban soils of Moscow (Smagin et al. 2006). This results in unfavorable conditions for flowers and green lawns with maximal root concentration in the surface layers. Degradation of the green lawns during the dry period of the year constrains the aesthetic value of urban areas, increases soil dust hazard, and has a negative influence on urban air quality. Misbalance in carbon cycle resulted from a very low photosynthetic activity at the degraded lawns reduce oxygen production increase carbon emission. Stability of soil cover and prevention of wind erosion (dust events) are also influenced by soil air-water regime.

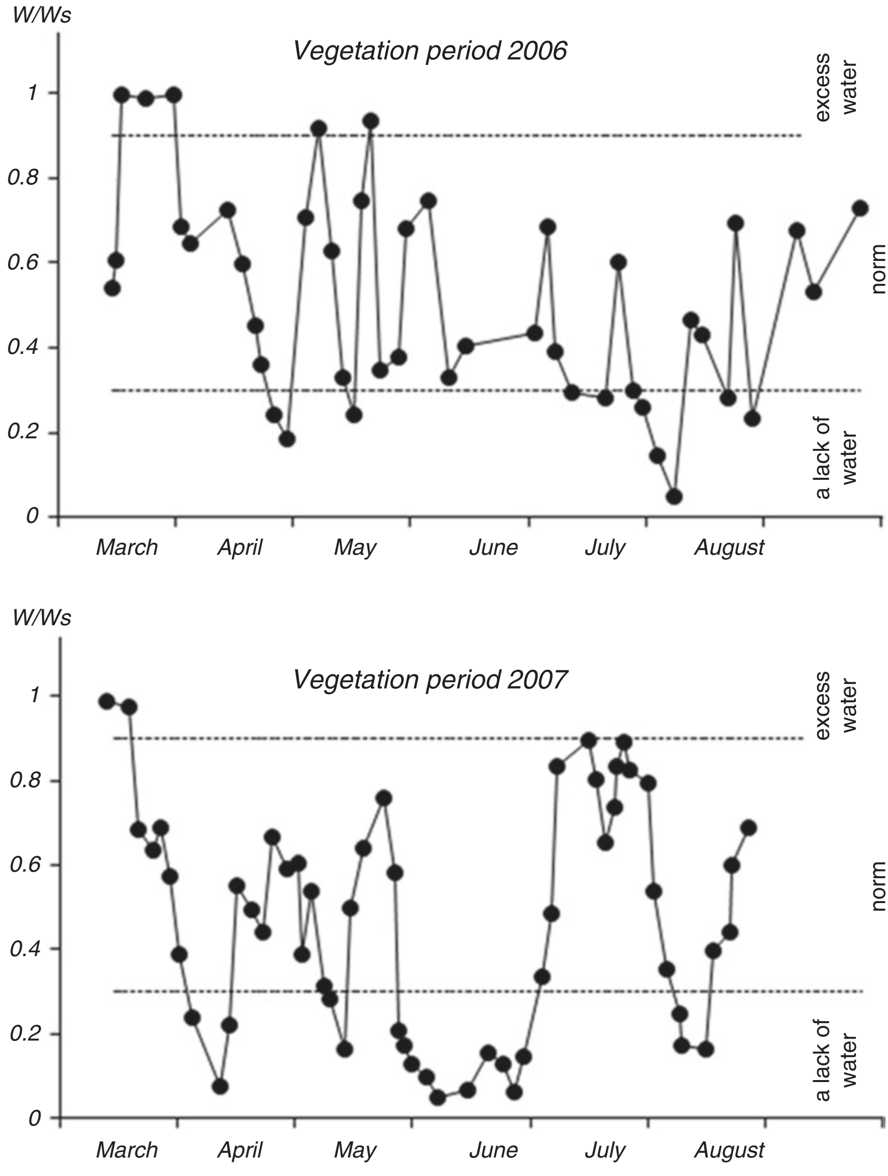


Fig. 18.2 Monitoring results of the urban soils' air-water regime (in the root layer) in the Moscow Zoo (W—soil moisture, Ws—complete water saturation, W/Ws—water saturation rate of pore space)

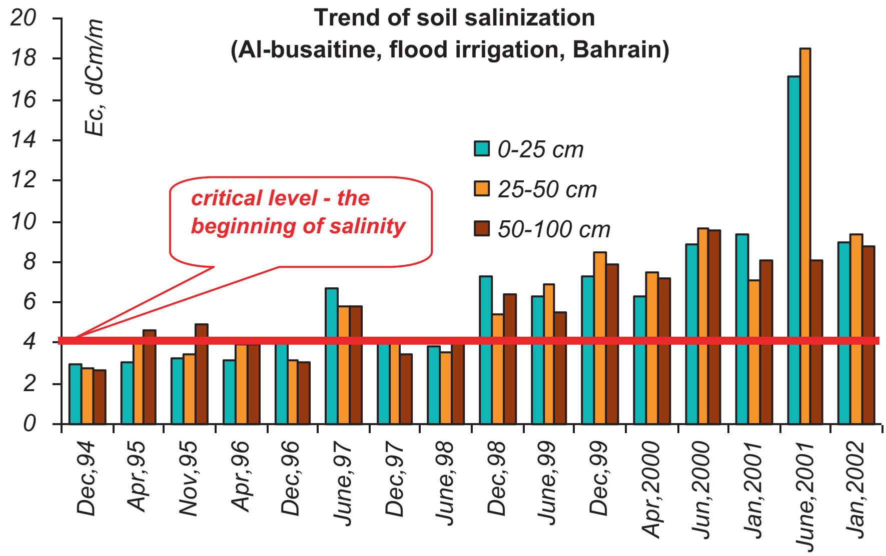
18.3.2.3 Monitoring Salt and Acid-Base Regimes in Urban Soils

Salinization is among the key anthropogenic pressures exposed by urban soils. It is resulted from active usage of "anti-ice" chemical substances and mineral fertilizers in urban management. Electroconductivity (Ec) of the pore solution is a relevant indicator of salinization (Smagin et al. 2006; Smagin 2012). An express assessment of urban soil's salinity and water availability for plants can base on Ec data, measured by portable conductometer-pH-meters (e.g., HI 98130 Combo HANNA). Estimating Ec of saturated pore solution (standard values) is based on measuring Ec for soil suspension in distilled water (usual dilution 1:5), with further multiplication of the results by 500/Ws coefficient (where Ws—is full water capacity). Solution pH is measured in parallel. This method was implemented by Smagin et al. (2006) to compare urban soils in arid and humid conditions as presented (Fig. 18.3). It's interesting that anthropogenic salinization from anti-ice substance in humid conditions of Moscow city can rise Ec up to 20–30 dSm/m, which is similar to the arid landscapes, where soil and water salinization are key environmental problems. Soil salinization, combined with soil and air pollution, caused high mortality of ornamental plants used in greenery works in Moscow in the late 1990s.

A gradual scale standardizing acid-base regime in urban soil is given in Table 18.4. Acid-base regime is monitored based on the pH value measured by conventional potentiometric method and filed or laboratory pH-meters. Acid-base regime of urban soils in Moscow likely deviates from optimal values (Table 18.4) at the central districts and at the roadsides. Accumulation of chemical "anti-ice" substances and building construction dust in urban soils shifts pH to alkaline zone. This depresses urban vegetation and meso- and microfauna of urban soils.

18.3.2.4 Monitoring Biological Activity and Respiration of Urban Soils

Potential biological activity is a very important parameter to assess the effectiveness of soil functioning. This parameter is usually estimated based on the soil respiration measurements in standardized optimal conditions (temperature 25–30 °C; 0.7–0.8 Ws, see detailed methodology for basal respiration (BR) in Sects. 18.4.4 and 18.4.5) (Smagin 2005). These standard conditions were determined based on the previous experiments, analyzing kinetics of biodestruction of soil organic matter in different thermodynamic conditions (Smagin 2005). Analyzing potential soil CO_2 emission (as it described for BR) is widely used to assess soil biological activity. An alternative approach measures oxygen uptake. This method allows eliminating interconnections between soil phases and therefore it is more relevant for mineral soils with low adsorption potential. We developed a gradual standard scale for the urban soils in Moscow city based on this approach (Table 18.5). This scale is implemented to monitor and assess urban soil's function to decompose different organic substrates, including plant residuals, sewage, faces, and domestic wastes. Combination of optimal temperature, air-water, salt and acid-base regimes with low biological activity likely indicates soil chemical or biological pollution. Alternatively, depressed vegetation combined with optimal potential biological activity likely indicates lack of nutrients or limited growing space that is a very often case for urban environment.



with the permission of the Ministry of Agriculture and Municipal Affairs of the Kingdom of Bahrain from (Smagin et al., 2005)

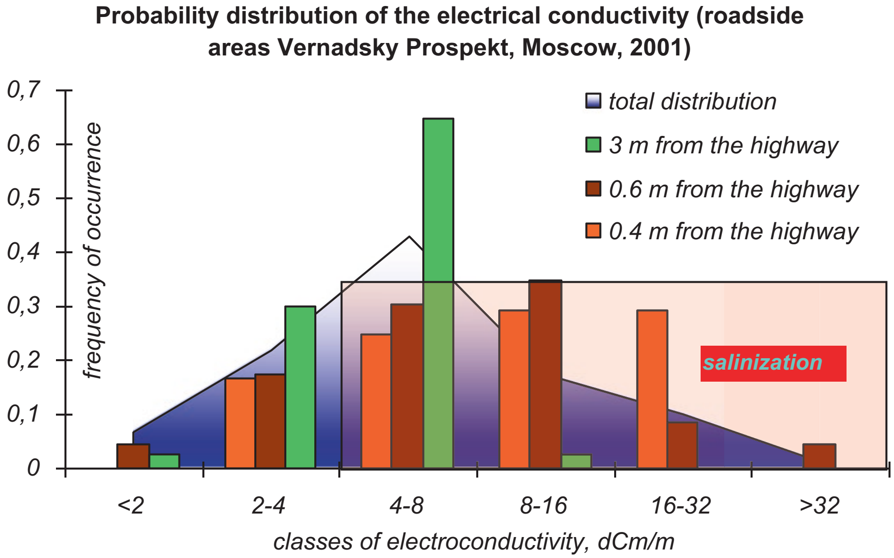


Fig. 18.3 Soil salinity assessed by conductometer (similar problems in the towns in arid and humid conditions)

Table 18.4 Standards to quantify salt and acid-base regimes of urban soils and soil constructions (Smagin et al. 2006)

Ec, dSm/m	Comments	pH	Comments
< 2 salinity is not indicated	Optimal for all plants	<4 very high acidity	Most of plants die; acid destruction of soil minerals ("podzolization")
2–4 very weak salinity	Only very sensible plants (roses, berries, apples, lilies) may have some damage	4–4.5 high acidity	Cultural plants are depressed; "podzolization" processes in the soil
4–8 weak salinity	Death of sensible species, productivity depression (up to 50%) for most non-tolerated plants; unfavorable physico-chemical alterations in the soil	4.5–5.5 moderate acidity	Optimal for coniferous boreal plants and mosses
8–16 moderate salinity	50–70% productivity depression of tolerated species (palms, cereals, tamarind, casuarinas, oleanders, salt bush, pomegranates, etc.) high degradation of soil	5.5–6.5 weak acidity	Optimal conditions for most plants, including cultural; coniferous and deciduous trees, grasses, and some vegetables
16–32 high salinity	Most of plants die; very high degradation of soil	6.5–7.5 neutral reaction	Optimal conditions for most plants, including cultural; coniferous trees are replaced by deciduous trees and grasses; optimal for most cultural vegetations
>32 very high salinity	Badlands; only very tolerated species (thorn tree, salty plants, sea plants) may live in such conditions	7.5–8.5 alkalinity	Most plants, including cultural have some damage; salinity and degradation of soil
		> 8.5 high alkalinity	High damage and death for most plants; only tolerated vegetation may survive; as a rule high soil degradation and salinity

18.3.3 Assessment of Environmental Functions Provided by Urban Soils in the Moscow Region

18.3.3.1 Introduction

Soil carbon stocks and microbiological activity are assumed to be sensitive and unbiased parameters for the assessment of soil environmental quality (Lorenz and Kandeler 2005; Creamer et al. 2014). Given the strong links between soil quality and functioning (Karlen et al. 1997;), these parameters are also suitable for the assessment of soil functions. This study aimed to assess soil functions in a very heterogeneous and highly urbanized Moscow Region, based on the proposed parameters. The results obtained for the urban soils were standardized by comparison with the natural references (Fedoroff 1987; Gil-Sotres et al. 2005).

Table 18.5 Standardized respiration for urban soils and soil constructions in Moscow (Smagin et al. 2006)

Potential respiration (mg O_2 kg^{-1} h^{-1})	Comments
0–2 very low biological activity	Absence or very low content of organic matter and microbes in soil; biological activity is depressed due to high pollution and salinity; soil is unfavorable for plantation
2–4 low biological activity	Low fertility of soil or (and) its depression by pollution and salinity; plants will be damaged and demand for fertilizing
4–8 moderate biological activity	Normal functioning of soil; optimal condition for most plants, including cultural
>8 high biological activity	High organic matter contents, microbes, and ferments concentration; if plant productivity and decay didn't compensate soil respiration, the soil can be degraded and is a substantial source of greenhouse gases' emission to atmosphere

18.3.3.2 Materials and Methods

The study focused on the Moscow Region, which is an interesting case study to analyze the influence of anthropogenic and bioclimatic factors on soil functions. The urban areas occupy more than 10% of its territory and continue to expand (Kachan et al. 2007). At the same time, the region exhibits a wide range of bioclimatic conditions including soil and vegetation (Shishov and Voinovich 2002). Three contrasting vegetation zones can be identified: south taiga, mixed forests, and forest steppe. Soil variation correlates strongly to these vegetation types with soddy-podzolic (Eutric Podzoluvisols), gray forest soils (Orthic Luvisols), and leached chernozems (Luvic Chernozems), respectively.

The procedure to quantify environmental functions provided by urban soils in Moscow Region included the following steps: (1) sampling of urban and reference natural soils; (2) chemical and microbiological analysis of soil features; (3) quantification of three soil functions through a comparison with reference standard soils of natural ecosystems, and (4) integral assessment of urban soils' functionality. Field data for the assessment of soil functions was collected in Moscow city and in four towns in Moscow Region, representing different bioclimatic conditions, soil types, and settlement history (Table 18.6). In each town three contrasting functional zones were observed: residential, recreational, and industrial. Natural pastures neighboring to the settlements were observed as a standard reference. Both topsoil (0–10 cm) and subsoil (10–150 cm) were analyzed.

The current study focuses on three soil functions: (1) habitat for microorganisms; (2) carbon sequestration; (3) substrate for plant growth. The soil *as a habitat for microorganisms* was assessed on the basis of the microbial carbon (C_{mic}) in comparison with reference standard soil under natural pasture. The C_{mic} was measured in standardized conditions by the substrate-induced respiration approach (Anderson and Domsch 1978; Ananyeva et al. 2008). The ratio between urban and natural C_{mic}

Table 18.6 Characteristics of Moscow city and settlements in Moscow Region

Settlement	Location (N/E)	Area (km^2)	Population (×1000)	Age (years)	Zonal vegetation type	Zonal soil (sub) type
Dubna	56°45′/37°09′	71.6	62.5	<50	South taiga	Peat-podzolic
Voskresensk	55°19′/38°41′	47	104.0	50–200	South taiga	Soddy-podzolic
Pushchino	54°50′/37°37′	17.8	20.0	<50	Mixed and deciduous forest	Gray forest
S. Prudi	54°27′/38°44′	3.7	8.9	200–500	Forest-steppe	Leached chernozems
Moscow	55°45′/37°37′	1097	10,381	50–900	South taiga	Soddy-podzolic

was estimated, expressed in % and graduated into five scores ranging from standard to very low. *Carbon sequestration* was described through carbon stock (soil organic carbon) and microbial respiration, measured in standardized conditions (basal respiration, BR), taken as proxy for the carbon flux. The function was quantified based on the difference of SOC stocks and MR respiration in analyzed and reference soils (see Vasenev 2011 for the detailed of quantification methodology). *The soil as a substrate for plant growth* was assessed using an agroecological index. This logistic function describes the relationship between soil productivity and soil chemical (C_{org}, pH_{KCl}, NO_3^-, NH_4^+, K_2O, P_2O_5, and heavy metals content) and physical properties (soil texture) (see Vasenev and Bukreyev (1994) for the methodological details). Soil standards were taken from the official recommendation on soil quality for green lawns, considering that urban soil cover is dominated by green lawns. All the results were expressed as mean ± standard deviation.

Two approaches were used for the assessment of integral soil functioning: experimental and statistical. An experimental approach assumed the analysis of the integral index qCO_2 (BR/C_{mic}) (Bastida et al. 2008), which is well accepted as an indicator of soil environmental quality (Insam et al. 1996; Vasenev et al. 2013a). High qCO_2 values are interpreted as an indicator of low ecosystem quality, whereas low values refer to optimal state (Insam et al. 1996; Liao et al. 2010). The values qCO_2 of urban soils were compared to reference natural soils and graduated to five scores, same as for the individual functions. The statistical approach was based on the harmonic mean of individual soil functions.

18.3.3.3 Results

Urban soils observed in different bioclimatic conditions of Moscow Region presented large variation, however, the difference between them and reference soils under pastures was significant (Fig. 18.4). Urban soils possessed higher carbon concentrations (especially for the subsoil) and nutrient contents (mainly for the topsoil) than natural ones. Heavy metal concentrations and pH_{KCl} were also higher for the urban environment, whereas microbial respiration and biomass was lower. Statistically significant difference between urban and natural soils in spite of very

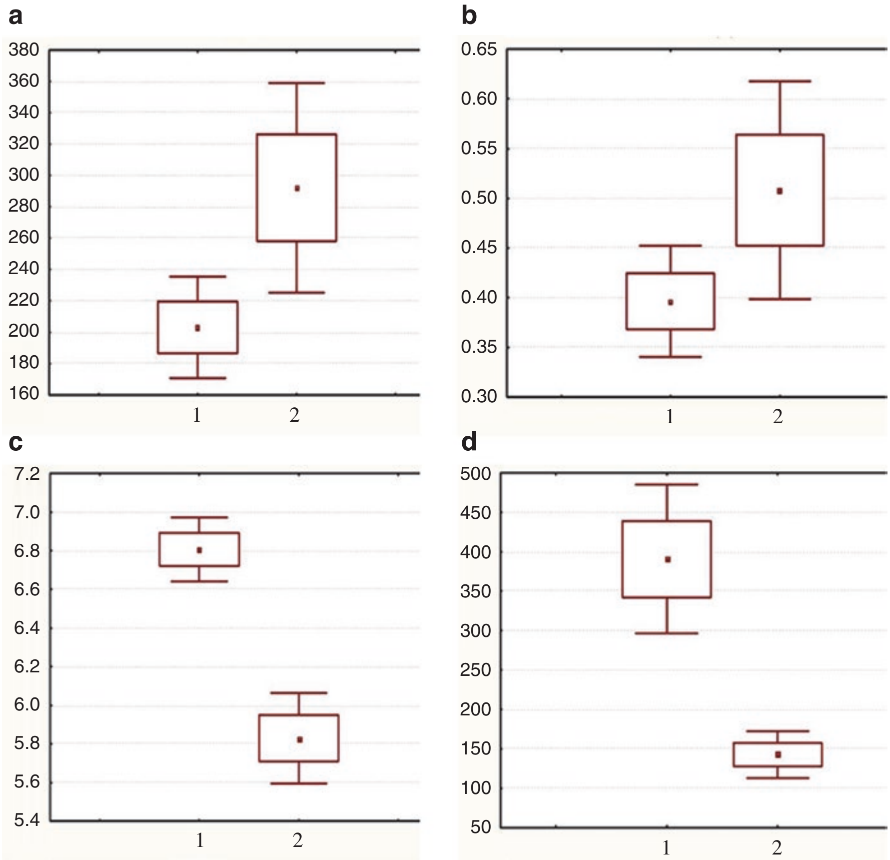


Fig. 18.4 Urban soil features in comparison to reference natural soils: mean, standard deviation and confident interval 95% for Cmic (A), MR (B), pHKCl (C) and P2O5 (D) in urban soils (1) and reference natural soil (2)

high internal heterogeneity is a vivid evidence of urbanization impact on soil features and environmental functions.

Urban soils from different settlements and functional zones inside the settlements were analyzed from the perspective of their environmental functions. Considering high variance between the features of reference soils from different bioclimatic zones, standardization based on reference soils was necessary to obtain results, comparable for different functions and settlements (Table 18.7). Topsoil's "habitat for microorganisms" function in average for the region was assessed as moderate (average score = 2.7; 28% of very low values for the region). The highest values were shown for Pushchino town and the lowest for Dubna settlement (average scores = 5.0 and 1.2 correspondingly). Urban soils in industrial zones performed the function significantly worse than ones in recreational and residential areas. In contrast, for the subsoil standard values of the function performance was reported

Table 18.7 Score scale for assessment of the individual urban functions of urban soils: as a habitat for microorganisms (function 1), carbon sequestration (function 2), substrate supporting plant growth (function 3), and for the integral assessment based on the experimental approach (Int_{qCO_2})

Score	Description	Deviation from the reference	Function 1[a]	Function 2[a]	Function 3[b]	Int_{qCO_2} [a]
5	Standard	No deviation	>95	<105	0.96–1.00	>95
4	High	Slight decline	80–94	105–120	0.75–0.96	80–94
3	Moderate	Intermediate declined	60–79	121–140	0.50–0.75	60–79
2	Low	Strong decline	30–59	141–170	0.25–0.50	30–59
1	Very low	Very strong decline	<29	>171	0.00–0.25	<29

[a]Ratio between the values of urban and reference soil functions (%)
[b]Scale of the agroecological index (Vasenev and Bukreyev 1994)

for 97% of the sampling locations. Performance of the carbon sequestration function in average for the region was assessed as very low for both topsoil (average scores = 2.1, 44% of very low values for the region) and subsoil (average scores = 2.4; 26% of very low values for the region). Soil as a substrate for plant growth was assessed as moderate in average for the region for the case of topsoils (average scores = 2.7; 44% of very low values). For subsoil lower average values were obtained (average score = 1.6 scores; 72% of very low values). The lowest scores were shown for the topsoil of Puschino and Voskresensk, whereas the maximum values were obtained for the subsoil of S. Prudi.

An integral assessment of urban soil's functioning, based on the qCO_2 values, standardized by natural references, was assessed as moderate for the topsoil (average scores = 2.8 scores; 38% of very low values) and low for the subsoil (average score = 1.8; 59% of the very low values). Values shown for urban topsoil in industrial areas were significantly lower than for ones in residential and recreational zones. As an alternative approach for integral assessment of urban soil functionality, harmonized mean of individual assessments was used. In average for the region both topsoil and subsoil functioning was assessed as very low (average score = 1.8 and 2.1 or 59 and 26% of very low values, respectively). The lowest results were shown for the Dubna settlement, the highest were reported for Voskresensk town and Moscow city (Table 18.8). Environmental functioning of urban soils in industrial areas was significantly worse than one in residential and recreational zones.

18.3.3.4 Discussion

The quantification results we obtained may be interpreted differently. On the one hand, in average for the region low and very low functionality was reported and strong negative effect of urbanization on soil environmental functions was demonstrated. On the other hand, high diversity of the values obtained for the individual functions performed by the same urban soils was shown. Thus only for the Dubna town the values for all individual and integral functional assessment were critical.

Table 18.8 The results of environmental assessment of individual functions (soils as a habitat for microorganisms (function 1), carbon sequestration (function 2), substrate supporting plant growth (function 3)), and integral assessment of urban topsoil/subsoil functionality in Moscow Region (based on the experimental (Int_{qCO_2}) and statistical (Int_{stat}) approach)

Settlement	Function			Int_{qCO_2}	Int_{stat}
	1	2	3		
Dubna	1.2 ± 0.4/5.0 ± 0.0	1.0 ± 0.0/1.9 ± 0.6	1.4 ± 1.0/1.0 ± 0.0	1.4 ± 0.7/1.8 ± 1.1	1.0 ± 0.0/1.8 ± 0.4
Moscow	2.9 ± 1.4/4.9 ± 0.8	2.9 ± 1.6/2.1 ± 1.3	2.6 ± 1.6/1.6 ± 1.2	3.0 ± 1.7/2.4 ± 1.6	2.3 ± 1.1/2.0 ± 1.2
Voskresensk	2.4 ± 1.6/4.6 ± 1.3	3.7 ± 1.7/2.2 ± 1.0	3.2 ± 1.8/1.8 ± 1.1	2.8 ± 2.1/1.8 ± 1.0	2.7 ± 1.3/2.2 ± 1.0
Pushchino	5.0 ± 0.0/5.0 ± 0.0	1.9 ± 0.7/3.7 ± 1.1	2.0 ± 1.7/1.0 ± 0.0	4.3 ± 1.3/1.0 ± 0.0	2.0 ± 0.8/2.0 ± 0.0
Serebrianie prudi	2.0 ± 0.9/5.0 ± 0.0	1.0 ± 0.0/2.7 ± 1.2	4.6 ± 1.3/1.6 ± 1.2	2.1 ± 1.1/1.1 ± 0.3	1.7 ± 0.5/3.0 ± 1.1

For other settlements critical values for one individual function were combined with optimal values for the other ones. For example, high quantity of soil microbiota results in optimal values of habitat of microorganisms function. At the same time soil microorganisms are responsible for the predominant part of CO_2 emission by soil, which may refer to decline in carbon sequestration function. Thus the results of integral assessment should be taken into account only considering the values, obtained for the individual functions' assessment. In comparison to traditional approaches for soil quality assessment, where all particular estimates are preliminary result for the final integral one, in case of the functional-environment assessment each individual function value is important

18.3.3.5 Conclusion

An approach for individual and integral quantification implemented in Moscow city and four settlements, located in different bioclimatic zones of Moscow Region, demonstrated high diversity of urban soil's functionality. In average for the region integral assessment results represented low values, however, for the individual functions and locations quantification results were very different and standard performance of one function could go together with low values of the other one by the same soil. Heterogeneity in urban soil's features and functions was mainly the results of different bioclimatic conditions, but also can be taken as the specific characteristic of urban environment. In contrast to many studies (Pouyat et al. 2006; Raciti et al. 2008; Ananyeva et al. 2008) we demonstrated important role of urban subsoil in performance of environmental functions. The values obtained for the subsoil were comparable and sometimes even higher than ones for the topsoil

18.3.4 Analyzing Spatial Variability of Microbiological Activity in Urban and Non-Urban Soils in the Moscow Region for Environmental and Economical Assessment of Soil Quality

18.3.4.1 Introduction

Microbiological processes in soils are very heterogeneous, therefore their spatial variability shall be studied at the different scales (i.e., micro locus, field, landscape, regional, and global) and as effected by different factors (relief, anthropogenic disturbance, and bioclimatic zone) (Bogoev and Gilmanov 1982; Parkin 1993; Zak et al. 1994; Morris and Boerner 1999; Saetre 1999; Yan et al. 2003). Few available studies relate spatial patterns of the microbial soil properties to the position in landscape (Walley et al. 1996), land-use type (Bloem and Breure 2003), season (Ross and Tate 1993), and soil treatment (Morris and Boerner 1999). High sensitivity of the soil microbial biomass content to environmental conditions and anthropogenic disturbances determines this parameter as a robust index to monitor and assess quality and functions of soils under different land-use (Anderson and Domsch 1986, 1989; DIN ISO 14240-1 1997; Winding et al. 2005; Sparling et al. 2004; Benedetti and Dilly 2006). However, spatial variability of microbiological parameters in urban soils is poorly studied, since the methodology and sampling design, relevant for the heterogeneous urban environment is lacking. The estimation of soil's microbiological activity parameters and their spatial variability provide an important background for the environmental and even economical assessment of soil quality.

In the study we developed the methodology to analyze spatial variability of soil microbiological parameters in heterogeneous areas and driving factors behind it (including bioclimatic conditions and soil chemical properties). The methodology was adapted for urban and non-urban soils in two districts of the Moscow Region. The analysis outcomes allowed estimating the microbiological index of soil quality. We compared the estimated microbiological index to the conventional soil ecological index to investigate the performance of both microbiological and agroecological parameters for the purpose of soil quality assessment. Finally, the estimated indexes were used to adjust the economical (cadastral) price of the land, considering the soil quality.

18.3.4.2 Material and Methods

Soil samples were collected in two districts located at the south of the Moscow Region, similar in climatic conditions (mean annual precipitation of 540–600 mm, and the accumulated mean daily temperatures for the growing season is 1800–2100 °C), but different in land-use structure. Agricultural and forest areas dominated in the Serpukhov district, whereas forest and urban areas gave together more than 80% of the Podolsk region. The Serpukhov district is dominated by soddy-podzolic, gray forest, and meadow-alluvial soils (Umbric Albeluvisols, Albic Luvisols, Fluvisols, respectively, according to WRB (2014)), whereas, gray forest soils in Podolsk district are rare. The uniform (grid-based) sampling design was implemented with grid cell of 2 km for Serpukhov and 5 km for Podolsk districts (Fig. 18.5). A topsoil

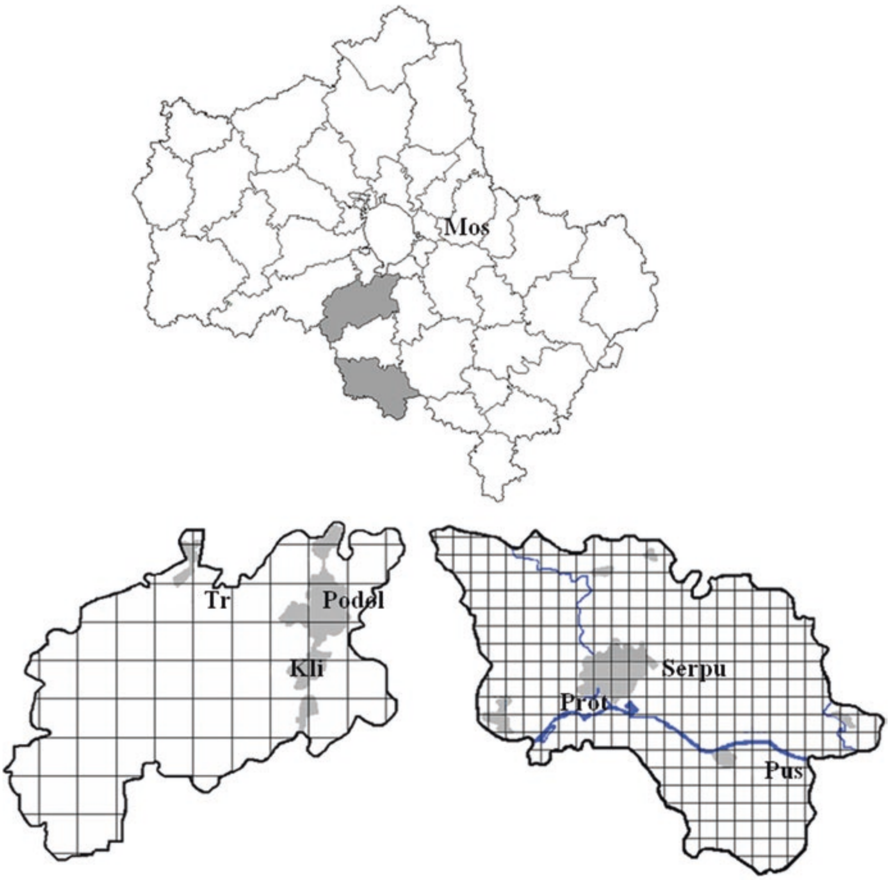


Fig. 18.5 Studied districts of Moscow Region (1—Podolsk, 2—Serpukhov) and soil sampling design

(0–10 cm) mixed sample (center and corners) was taken from the mineral layers at 10 by 10 m plots from each of the grids. Overall, 282 soil samples were taken from three urban (lawn, city park, and industrial area) and three non-urban (forest, fallow and arable) land-use types. Soil samples at natural moistening were kept at 8–10 °C for no longer than 2 months. Before the analyses, the samples were sieved (2-mm mesh) and preincubated.

In the collected samples Corg content was determined by the method of dichromate oxidation (wet combustion); the soil pH was determined in water suspension (soil:water = 1:2.5), and the particle-size distribution analysis was performed by the gravimetric method with the soil pretreatment with sodium pyrophosphate (Arinushkina 1970). The substrate-induced respiration (SIR) and basal respiration (BR) were measured in the samples following the standard methodology (Anderson and Domsch 1978; Ananyeva et al. 2008). *Soil microbial biomass carbon* (C_{mic}) was determined from the SIR data using the following equation: C_{mic} (μg C g^{-1} soil) = SIR (μL CO_2 g^{-1} soil h^{-1}) × 40.04 + 0.37 (Anderson and Domsch 1978). The relative indexes of soil microbial community functioning were calculated: *specific respiration of soil microbial biomass* or microbial metabolic quotient as the ratio of BR to microbial biomass (qCO_2, μg CO_2–C mg^{-1} C_{mic} h^{-1}) and the *portion soil microbial biomass carbon* (C_{mic}) in *soil total organic carbon* (C_{mic}/C_{org}, %). All the measurements were taken in four replicates, mean values ± standard deviations were calculated per dry soil (105 °C, 8 h).

Collected bioclimatic data and measured soil chemical and physical features were used to estimate the soil ecological index (SEI) (Karmanov 1989), comprising physicochemical, agrochemical, and climatic scores. SEI ranges from 0 to 100 with 100 for the highest ecological soil quality (see Savich et al. 2003 and Gavrilenko et al. 2013 for the detailed methodology). The obtained SEI values were used to estimate the soil price as the product of SEI and the tariff category (Rubles ha^{-1}), depending on the land-use type and expected profit from the land-use (Karmanov 1989, 1991). The estimated price was adjusted using a correction coefficient of SEI, considering soil microbial biomass carbon.

18.3.4.3 Results

High spatial variability in chemical and microbiological features, reported for the research districts, was determined by various ecosystems and soil types. For example, the highest C_{mic} and BR values were obtained for the forest, compared to arable and urban areas. The mean C_{mic}/C_{org} values of arable and urban soils were significantly lower compared to forest and fallow. The C_{mic} and BR in meadow-alluvial and urban soils were significantly lower than in soddy-podzolic soils in the Podolsk district. In the Serpukhov district the highest C_{mic} was found in soddy-gley soils, whereas the highest BR was observed in bog-podzolic and soddy-gley soils. Meadow-alluvial and urban soils possessed the lowest C_{mic} and BR (Tables 18.9 and 18.10). The highest qCO_2 was found for forest ecosystems, whereas qCO_2 for the arable soils in Serpukhov district was the lowest. The mean qCO_2 value (averaged for the two districts) under coniferous forests was significantly higher than that under mixed and deciduous forests (2.97; 2.31 and 1.74 μg CO_2–C mg^{-1} C_{mic} h^{-1}, respectively). The lowest significant mean C_{mic}/C_{org} values were observed in the arable and urban soils of studied districts, whereas the highest—in forest and fallow ecosystems (Tables 18.11 and 18.12). Relationships between microbiological activity, soil type, ecosystems, and relief elements have been estimated by the three-way ANOVA. The highest contribution in C_{mic} and BR variance belongs to “ecosystem” factor (50 and 80%, respectively), and the lowest one was shown for the “soil” (30 and 9%, respectively).

Obtained soil chemical and physical features incorporated with the bioclimatic data were standardized and ranked to estimate SEI. The SEI values for the studied soils ranged from 28.4 to 98.5 scores. The average values for the fallow and cropland ecosystems were significantly higher than those for the forest ecosystems (Table 18.13). The most significant variation in the SEI (28.4–82.0) was observed for the forests and fallows (39.2–98.5). In the group with the low SEI (≤50), a

Table 18.9 Soil organic carbon content (C_{org}) and soil pH in different soils (0–10 cm) of Podolsk (P) and Serpukhov (S) districts of Moscow Region (value with different letters significantly differ, $p \leq 0.05$, for each column separately)

Soil[a] (number sites, P/S)	C_{org}, % (range/mean)		Soil pH_w, (range/mean)	
	Podolsk	Serpukhov	Podolsk	Serpukhov
MA (3/24)	0.87–1.25/1.08 *a*	0.50–3.29/1.76 *a*	7.60–7.90/7.72 *b*	6.30–8.05/7.33 *d*
GF (0/56)	Not found	1.04–4.22/2.20 *ab*	Not found	5.37–7.29/6.21 *c*
SP (34/133)	0.96–4.43/2.38 *b*	0.38–5.14/2.49 *ab*	4.43–7.44/5.57 *a*	4.02–7.70/5.30 *b*
U (8/16)	1.10–3.65/2.49 *b*	1.35–10.11/3.23 *b*	6.64–7.85/7.42 *b*	5.91–8.29/7.31 *d*
SG (0/4)	Not found	6.84–9.40/7.72 *c*	Not found	5.64–6.70/6.33 *c*
BP (0/4)	Not found	10.03–27.66/15.29 *d*	Not found	3.70–4.25/4.01 *a*

[a]*MA* meadow-alluvial, *GF* gray forest, *SP* soddy-podzolic, *U* urban, *SG* soddy-gley, *BP* bog-podzolic

Table 18.10 Soil microbial biomass carbon (C_{mic}) and soil basal respiration (BR) of different ecosystems in Podolsk (P) and Serpukhov (S) districts of Moscow Region (value with different letters significantly differ, $p \leq 0.05$, for each column separately)

Ecosystem (number site, P/S)	C_{mic}, μg C g^{-1} (range/mean)		BR, μg CO_2-C g^{-1} soil h^{-1} (range/mean)	
	P	S	P	S
Arable (4/13)	43–318/155 *a*	72–252/150 *a*	0.06–0.74/0.39 *a*	0.06–0.42/0.18 *a*
Urban (8/16)	67–566/274 *a*	47–392/214 *ab*	0.09–0.77/0.38 *a*	0.14–0.56/0.35 *ab*
Fallow (8/82)	166–530/365 *a*	53–883/314 *b*	0.17–0.92/0.61 *a*	0.16–1.12/0.49 *b*
Forest (25/126)	173–1394/637 *b*	58–1366/530 *c*	0.34–3.25/1.15 *b*	0.19–2.43/0.95 *c*

significant part (86%) belongs to forest soils. In the forest soils, the significant lowest SEI was under pine forests, whereas the highest SEI corresponds to the predominance of leaved species. The spatial visualization of SEI for studied region was carried out (Fig. 18.6), which showed larger heterogeneity of SEI in the Serpukhov district (28.4–98.5 scores) compared to the Podolsk (41.7–82.7 scores). The contribution of different factors to SEI variance of studied soils was estimated by the three-way ANOVA. The most significant contribution to SEI total variance was shown for "soil," "ecosystem," and "relief" factors (45, 20, and 17%, respectively). The relationships between the SEI values and the physicochemical and microbiological characteristics of the studied soils were assessed by correlation analysis. The relationships between SEI and the microbiological characteristics (C_{mic}, BR, qCO_2, C_{mic}/C_{org}) were significant for forest soils, urban soils (C_{mic}, qCO_2, C_{mic}/C_{org}), arable (BR, C_{mic}/C_{org}), and fallow soils (C_{mic}, qCO_2). For forest soils, the relationship between SEI and microbiological indices (C_{mic}, C_{mic}/C_{org}, qCO_2) is approximated by the corresponding equations with significant coefficient of determination (Fig. 18.7).

Table 18.11 Soil microbial metabolic quotient (qCO_2, μg CO_2–C mg^{-1} C_{mic} h^{-1}) of different soil (0–10 cm) ecosystems, and relief elements in Podolsk (P) and Serpukhov (S) districts (value with different letters significantly differ, $p \leq 0.05$, for each column and each parameter separately)

Number site (P/S/ P + S)	P	S	P + S
Ecosystem			
Arable (4/13/17)	1.46–4.03/2.32 *a*	0.64–1.79/1.14 *a*	0.64–4.03/1.42 *a*
Fallow (8/82/90)	0.99–2.86/1.72 *a*	0.68–3.40/1.76 *b*	0.68–3.40/1.76 *a*
Urban (8/16/24)	1.08–2.37/1.56 *a*	0.90–3.78/1.95 *b*	0.90–3.78/1.82 *ab*
Forest (25/126/151)	1.08–3.14/1.84 *a*	0.34–6.52/2.31 *b*	0.34–6.52/2.23 *b*
Soil[a]			
SG (0/4/4)	Not found	0.34–2.03/1.15 *a*	0.34–2.03/1.15 *a*
MA (3/24/27)	0.99–1.85/1.44 *a*	0.64–3.40/1.41 *a*	0.64–3.40/1.41 *ab*
GF (0/56/56)	Not found	0.60–2.88/1.57 *ab*	0.60–2.88/1.57 *ab*
BP (0/4/4)	Not found	1.33–2.11/1.88 *ab*	1.33–2.11/1.88 *ab*
U (8/16/24)	1.08–2.37/1.56 *a*	0.90–3.78/1.95 *ab*	0.90–3.78/1.82 *ab*
SP (34/133/167)	1.08–4.03/1.91 *a*	0.82–6.52/2.38 *b*	0.82–6.52/2.28 *b*
Relief			
Floodplain (0/21/21)	Not found	0.64–2.95/1.24 *a*	0.64–2.95/1.24 *a*
Upper slope (13/76/89)	1.08–2.16/1.62 *a*	0.82–4.00/1.84 *b*	0.82–4.00/1.81 *b*
Middle slope (15/52/67)	1.20–4.03/2.09 *a*	0.34–5.26/2.09 *b*	0.34–5.26/2.09 *b*
Watershed (12/65/77)	1.08–2.97/1.78 *a*	0.60–5.12/2.14 *b*	0.60–5.12/2.08 *b*
Low slope (5/23/28)	0.99–2.41/1.60 *a*	1.12–6.52/2.96 *c*	0.99–6.52/2.72 *c*

[a]See Table 18.9

The obtained SEI values were used to estimate the soil price in the investigated districts, considering an appropriate tariff category from 1991 (the year when the tariffs were officially fixed for the last time) (Gavrilenko et al. 2011, 2013). The calculated soil price of different studied ecosystems is given in Table 18.14. The price of arable soil was in average significantly ($p \leq 0.05$) higher than that of fallow soil. The soil price under woody stands (forest) was significantly higher than that of grassy (fallow + arable) ones. Therefore one would assume that forest soils should be evaluated higher than those, for example, of arable and fallow lands, since their physical and chemical properties and ecological functions are preferable. The influence of the "forest type" and "soil" on the price of forest soils for studied districts was analyzed by ANOVA. Both factors ("forest type" and "soil") were significant and determined by 33 and 55% of the total variance, respectively.

SEI characterizes soil physicochemical properties and regional climatic conditions. Soil biological property might be characterized by soil microbial biomass content, expressed as soil microbial biomass carbon (C_{mic}). A positive significant correlation of SIE with C_{org} and C_{mic}/C_{org} ratio was found for forest soils of the studied region. Therefore, we used a correction coefficient of SEI, considering soil microbial biomass carbon, to assess the soil price for different ecosystems (forest, fallow, arable). The average soils price in the Podolsk and Serpukhov districts of the Moscow Region were almost 18,000, 8500, and 4300 Rubles ha^{-1} (in 1991 year.) for

Table 18.12 Portion of microbial biomass carbon in total soil organic carbon (C_{mic}/C_{org}, %) of different soil (0–10 cm) ecosystems, and relief elements in Podolsk (P) and Serpukhov (S) districts (value with different letters significantly differ, $p \leq 0.05$, for each column and each parameter separately)

Number site (P/S/P + S)	P	S	P + S
Ecosystem			
Urban (8/16/24)	0.42–1.86/1.05 *a*	0.19–1.41/0.77 *a*	0.19–1.86/0.86 *a*
Arable (4/13/17)	0.50–1.89/1.19 *a*	0.55–1.98/1.02 *a*	0.50–1.98/1.06 *a*
Fallow (8/82/90)	1.33–4.03/2.40 *b*	0.32–5.10/1.75 *b*	0.32–5.10/1.81 *b*
Forest (25/126/151)	0.70–3.36/2.39 *b*	0.22–10.65/1.88 *b*	0.22–10.65/1.96 *b*
Soil[a]			
BP (0/4/4)	Not found	0.36–0.59/0.49 *a*	0.36–0.59/0.49 *a*
U (8/16/24)	0.42–1.86/1.05 *a*	0.19–1.41/0.77 *ab*	0.19–1.86/0.86 *ab*
MA (3/24/27)	0.50–1.33/0.83 *a*	0.42–3.11/1.22 *ab*	0.42–3.11/1.17 *ab*
SG (0/4/4)	Not found	1.01–1.86/1.44 *abc*	1.01–1.86/1.44 *abc*
SP (34/133/167)	0.70–4.03/2.39 *b*	0.22–10.65/1.67 *bc*	0.22–10.65/1.82 *bc*
SG (0/56/56)	Not found	0.67–5.72/2.39 *c*	0.67–5.72/2.39 *c*
Relief			
Low slope (5/23/28)	0.42–1.53/0.89 *a*	0.27–3.11/1.05 *a*	0.27–3.11/1.02 *a*
Floodplain (0/21/21)	Not found	0.55–2.49/1.20 *a*	0.55–2.49/1.20 *ab*
Middle slope (15/52/67)	0.58–4.03/2.20 *b*	0.22–4.71/1.46 *ab*	0.22–4.71/1.62 *bc*
Watershed (12/65/77)	0.54–3.20/1.81 *b*	0.19–10.65/1.81 *bc*	0.19–10.65/1.81 *cd*
Upper slope (13/76/89)	1.89–3.15/2.53 *b*	0.37–6.22/2.14 *c*	0.37–6.22/2.20 *d*

[a]See Table 18.9

Table 18.13 Soil ecological index (SEI) of different ecosystems in Serpukhov (S) and Podolsk (P) districts (value with different letters significantly differ, $p \leq 0.05$, for each column separately)

Ecosystem (number sites, P/S/P + S)	SEI, score (range/mean)		
	Podolsk	Serpukhov	P + S
Forest (25/126/151)	54.2–64.6/59.5 *a*	28.4–82.0/53.3 *a*	28.4–82.0/54.4 *a*
Urban (8/16/24)	50.8–82.7/70.3 *b*	43.7–88.7/61.2 *b*	43.7–88.7/64.2 *b*
Fallow (8/82/90)	41.7–81.8/67.2 *ab*	39.2–98.5/70.5 *c*	39.2–98.5/70.2 *bc*
Arable (4/13/17)	58.2–79.3/68.4 *b*	53.3–91.6/74.2 *c*	53.3–91.6/72.8 *c*

forest, fallow, and arable ecosystems, respectively (Fig. 18.8; Table 18.15). The spatial distribution of soil prices calculated basis on SEI, tariff category, correction biological coefficient in the Podolsk and Serpukhov districts of the Moscow Region is shown in Fig. 18.8. Incorporating of the soil biological properties in the soil price estimates enables considering both economical and environmental soil quality.

18.3.4.4 Discussion

Soil microbial biomass carbon is an important characteristic of soil functions (Anderson and Domsch 1989; Wardle 1992; Bölter et al. 2002). It was proved that the microbial biomass is more sensitive to environment changes than the soil organic

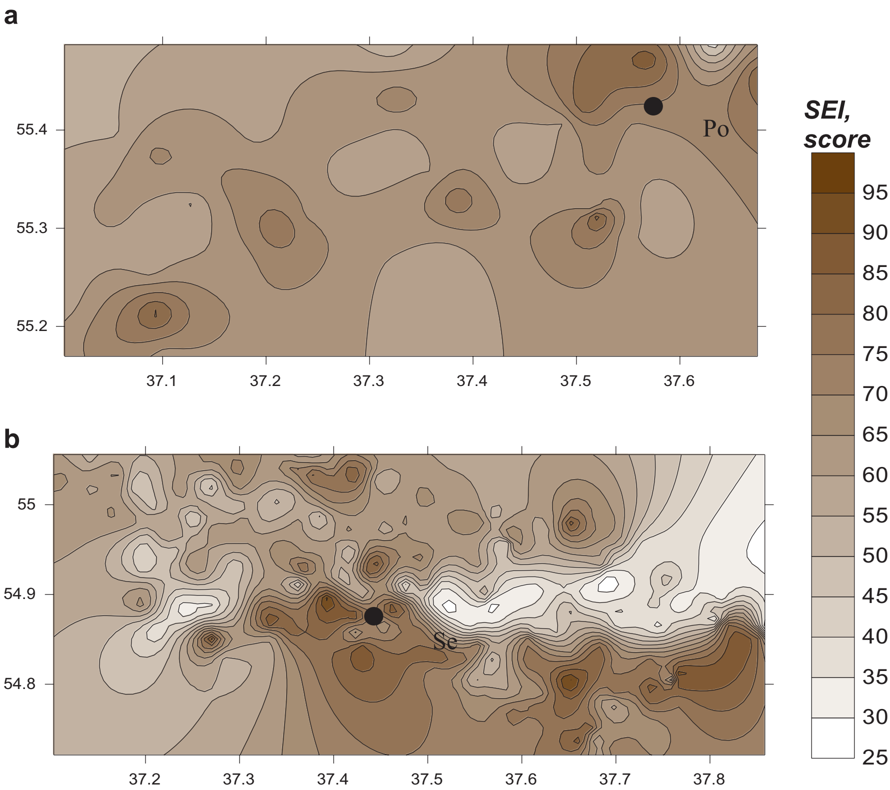


Fig. 18.6 The soil ecological index (SEI) distribution in Podolsk (**a**) and Serpukhov (**b**) districts of Moscow Region (axis X is E°, axis Y is N°)

matter content (Franzluebbers et al. 1995; Hargreaves et al. 2003). In addition, soil microbial biomass is a reliable indicator of crop yields (Jordan et al. 1995). Basal respiration of soil microorganisms indicated an availability of soil organic carbon. Although the microbial respiration at natural (field) conditions is highly variable (Cook and Greaves 1987; Martin and Bolstad 2009), mainly due to changes of hydrothermal conditions, under laboratory conditions (40–60% water holding capacity, 15–25 °C), soil respiration may be accurately and precisely determined. In our study, BR was less "sensitive" to ecological factors than C_{mic}, though there is a close positive correlation between these parameters.

Investigated soil microbiological parameters complemented more conventional physicochemical characteristics for soil quality assessment through the SEI index. The methodology of SEI estimation suggested by Karmanov (1989) was initially designed for agricultural soils and focused on the soil fertility. We expanded the implementation of the index to estimate soil quality for different ecosystems. The higher SEI values obtained for the arable lands compared to the forest areas were likely caused by the main attention given to agrochemical features (i.e., nutrient

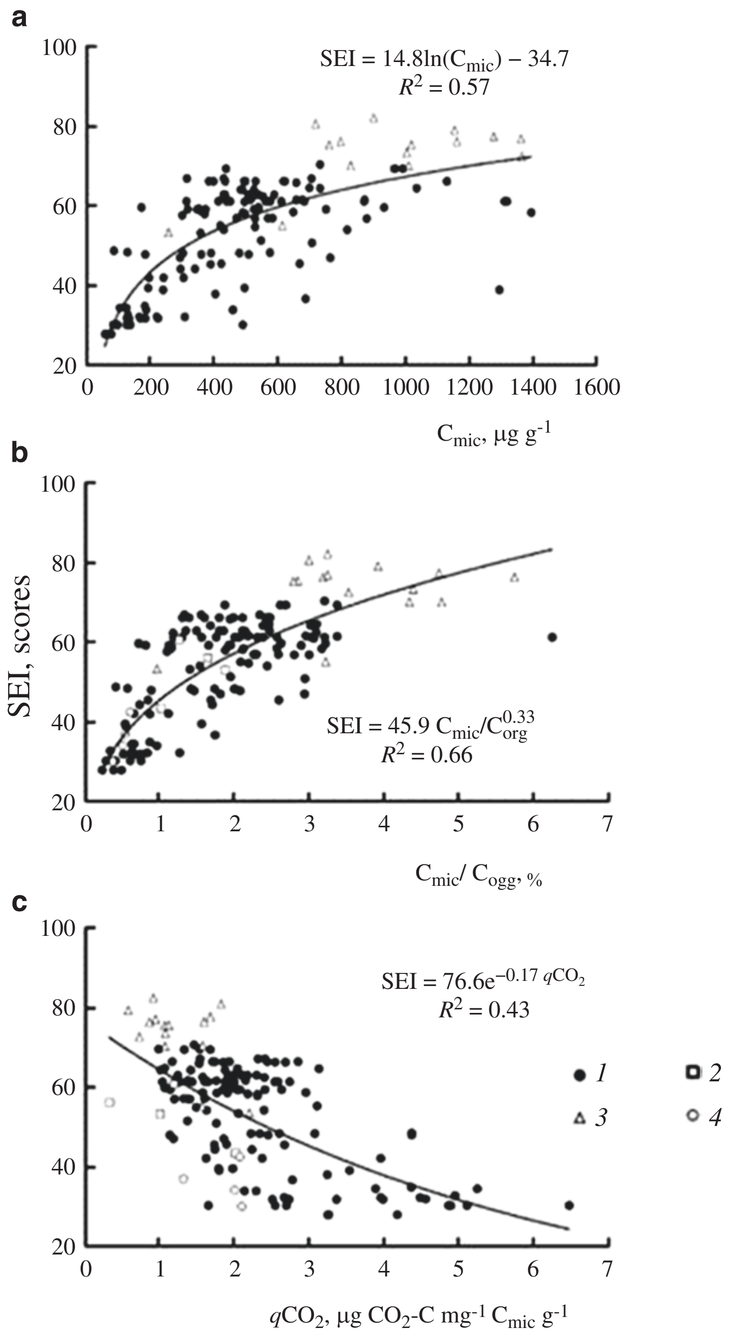


Fig. 18.7 Relationships between soil ecological index (SEI) and soil microbial biomass carbon (C_{mic}, $n = 143$, bog-podzolic and soddy-gley soils are excluded) (**a**), and portion of soil microbial biomass carbon in total organic carbon (C_{mic}/C_{org}, $n = 148$) (**b**), and microbial metabolic quotient (qCO_2, $n = 149$) (**c**) for forest soils of Moscow Region: (1) soddy-podzolic, (2) gray forest, (3) soddy-gley, (4) bog-podzolic

Table 18.14 Soil price (1991 yr.) of different ecosystems in studied Serpukhov and Podolsk districts, calculated on basis of soil ecological index and tariff category (value with different letters significantly differ, $p \leq 0.05$)

Ecosystem (number sites)	Soil price, Rubles ha^{-1} (range/mean)
Forest (151)	9358–27,068/17,935 *b*
Fallow (90)	5494–27,352/12,071 *a*
Arable (17)	8154–25,659/18,469 *b*
Fallow + Arable (107)	5494–27,352/13,087 *a*

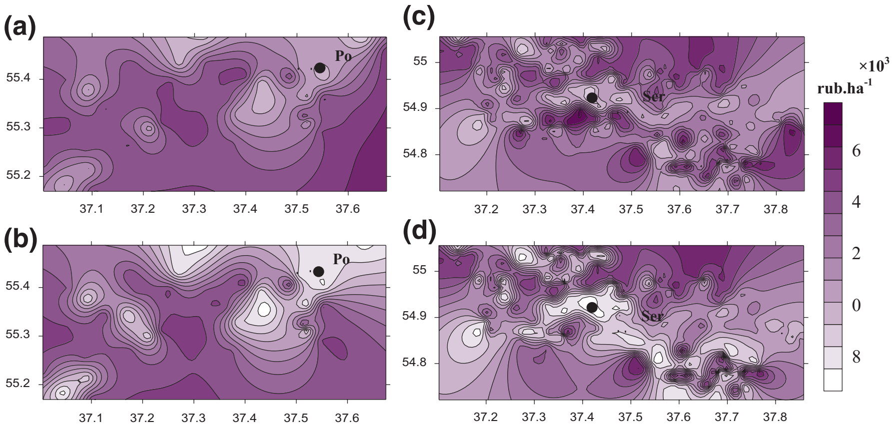


Fig. 18.8 Distribution of soil price in the Podolsk (**a**, **b**) и Serpukhov (**c**, **d**) districts of the Moscow Region calculated by multiplication of soil ecological index and tariff category (**a**, **c**) and by biological correction coefficient (**b**, **d**)

Table 18.15 Soil price (1991 yr.) of different ecosystems in Serpukhov and Podolsk districts calculated on basis of soil ecological index (SEI), correction coefficient (CC, for forest it equal 1), and tariff category (value with different letters significantly differ, $p \leq 0.05$, for SEI and C_{mic} separately)

Ecosystem (number sites)	SEI, score	C_{mic}, μg C g^{-1} soil	CC	SEI* (SEI × CC), score	Tariff category (T)	Price (SEI* × T)
					Rubles ha^{-1}	
Forest (151)	54.4 *a*	548 *c* (I)	1 (I/I)	54.4	330	17,952
Fallow (90)	70.2 *b*	319 *b* (II)	0.58 (II/I)	40.7	210	8551
Arable (17)	72.8 *bc*	152 *a* (III)	0.28 (III/I)	20.4	210	4280

concentration and soil texture) in the estimation of SEI. Considering lower nutrients' supply and acid pH of the forest soils, the SEI values obtained for the forest soils were relatively low. However, taking into account the high ecological significance of forest soils, an underestimation is very likely. To avoid this underestimation we implemented a corrective biological coefficient, based on the close correlation between SEI and soil microbiological characteristics (C_{mic}, C_{mic}/C_{org})

found for different land-use types in the research area. The SEI values in fallow, arable, and urban areas were standardized based on the C_{mic} for the corresponding land-use related to the C_{mic} for the forest taken as a natural reference. For example, C_{mic} averaged for the urban areas in the region was 152 μg C g^{-1}, which was just 43% from the forest C_{mic} (548 μg C g^{-1} soil), giving the correction coefficient 0.43. Therefore, the SEI averaged for the forest, fallow, urban and arable soils calculated with due account for C_{mic} should be equal to 54.4 (54.4 × 1.00), 40.7 (70.2 × 0.58), 27.6 (64.2 × 0.43), and 20.4 (72.8 × 0.28) scores, respectively.

The average SEI obtained for the urban soils were higher than that in forest ecosystems (64 and 54 scores, respectively). It should be taken into account that the most urban soils had the high supply of available nutrients (32.3 mg 100 g^{-1} soil for P_2O_5 and 16.7 mg 100 g^{-1} soil for K_2O) and high pH value (7.3). However, the microbiological parameters (C_{mic}, C_{mic}/C_{org}, BR) of urban soils were significantly lower than those of natural ecosystems (fallow, forest). Thus, the SEI-based ranking (arable > fallow > urban > forest) can be transformed to the other one (forest > fallow > urban > arable) when the correction coefficient was implemented. The new rating of soil quality for different ecosystems considering for their biological properties is more reliable from the ecological point of view.

The same underestimation of the forest soils over croplands was shown for the soil price estimation. Low cadastral prices traditionally given to the forest lands compared to agricultural lands in the result of soil features and functions' ignorance. For example, the cadastral price of the forest land based on wood species productivity ignore soil ecological functions conservation, oxygen production, toxins absorption, water and wind erosion prevention, microclimate regulation, that underestimates the value of the forest soils for environment and society (Shimanuk 1974; Savich et al. 2003; Dobrovolskii and Nikitin 2006; Makarov and Kamanina 2008). Therefore, the proposed approach of cadastral assessment based on the soil ecological index, tariff category, and biological correction coefficient gives a promising tool to consider soil quality and functions in land assessment.

18.3.4.5 Conclusion

Although high spatial variability in soil chemical, physical, and microbiological features was observed, significant difference in soil quality and performed soil functions was found between different land-use types: forest, cropland, and urban. Urban environment was not favorable for soil microorganisms, which was clearly shown by low microbiological activity parameters (C_{mic} and BR) and integral indexes (qCO_2 and C_{mic}/C_{org}). The ecological and economical value of urban soils estimated by the integral soil ecological index adjusted by the microbial correction coefficient was comparable to arable and fallow land, but was substantially less than in the natural areas, clearly indicating that investigate soils' functions (i.e., habitat for microorganisms and maintaining biodiversity) are not properly performed in urban areas. Taking into account additional soil functions, like carbon sequestration or run-off purification, would be necessary for a more comprehensive assessment of urban soils' quality and functions.

18.4 From Functional Assessment towards Best Management Practices to Maintain Urban Soils' Quality

18.4.1 Introduction

Urban soils are key components of urban ecosystems, therefore successful management of urban green infrastructure is impossible without considering soil quality. Most of the traditional practices in urban greenery and accomplishment lack attention to urban soil's function. Ignoring soil information in urban management practices likely results in soil and run-off contamination, emission of greenhouse gases and particle matters, degrading of urban vegetation. In this section we present different implementations of knowledge of urban soil quality and functions to manage urban ecosystems. Different technologies of urban soil's management are presented. Section 18.4.2 reviews rather straightforward practices to manage soils contaminated with heavy metals. Recommended practices are aggregated in a straightforward advice list for gardeners and landowners. Automated intellectual system described in Sect. 18.4.3 is a more complicated approach to distinguish the best management practices for urban soils depending on their functional use and disturbance level. Finally, Sect. 18.4.4 reviews different technologies of urban soil's constructions, representing the most radical approach of urban soil management by creating soil construction with the pre-given features to meet specific requirements (e.g., preserving ground water from contamination or maintaining green lawns in water scarcity conditions). The relevance of the proposed management practices is illustrated by the examples from New York, Moscow, and Dubai, where they were successfully implemented.

18.4.2 Framework Best Management Practices for Contaminated Urban Soils

Soil contamination is an important consideration when designating certain land for different uses. In general, industrial and commercial use of the lands are the least stringent in standards, while those for close human contact (such as food producing gardens and children playgrounds) should contain as little contaminants as possible. In many cases, instead of trying to remediate the soils that are often very expensive, careful soil survey and land-use planning (i.e., zoning designation) are the first step in reducing human health risk from urban soil contamination (Urban Soil Primer 2005). Different land uses require different managing strategies (Fig. 18.9). Human, animal, and ecological risk must be evaluated for any given site. Costs must be taken into consideration when developing short-term and long-term strategies.

For general use with minimal human interaction (e.g., forests, parks, recreation areas), maintaining a vegetated cover is important to limit the spread of contaminated soils by running water or wind. For ornamental gardens, cover crops can be very beneficial. They reduce nutrient leaching, increase fertility and organic matter content, suppress soil diseases and pests, attract beneficial insects and microbes, fix

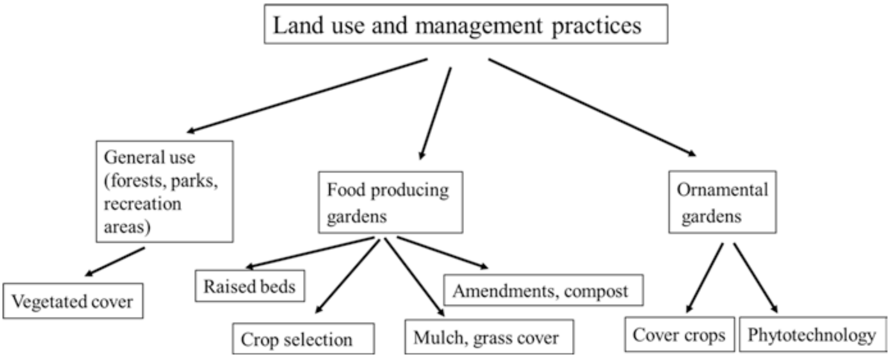


Fig. 18.9 Managing strategies required for different land uses

nitrogen, prevent soil erosion, and improve drainage and water retention in soils (Gugino et al. 2009).

Other strategies that can be applied in contaminated ornamental gardens are phytotechnologies. Phytotechnologies are a set of techniques that incorporate plants to remove, degrade, hold, or immobilize contamination in soil, groundwater, or surface water (Paz-Alberto et al. 2013). Climate, elevation, soil type and quality, properties of contaminates, and the capability of the plants and planting system used for each location influence the success and economic feasibility of a phytotechnology (EPA 542-F-10-009). For food producing gardens, contaminants can pose health risk through direct ingestion of soil or dust, or through the consumption of contaminant-bearing produce. Therefore, limiting both pathways are important. The Healthy Soils Healthy Communities Project, a partnership among Cornell University, New York State Department of Health and New York City Green Thumb, develop the ten Best Management Practices for urban gardeners: (1) use clean soil and compost; (2) use raised beds; (3) avoid treated wood; (4) maintain soil nutrients and pH; (5) cover (or mulch) soil; (6) keep an eye on children; (7) leave the soil in the garden; (8) wash your hands; (9) wash and/or peel produce; (10) put a barrier under play areas.

Most often, a physical barrier between contaminated ground soil and gardeners can be created by the addition of clean soil and organic matter placed within bed frames. Walkways can be covered with mulch or grass to protect children from exposure (EPA 542-F-10-009; Mitchell et al. 2014). The use of raised beds for urban produce gardens has been employed as an exposure reduction method for decades. They protect produce from weed invasion, avert soil compaction, provide good drainage, and serve as a barrier to pests (slugs and snails). Plant selection is an important consideration for gardening in contaminated soils. Usually, fruiting plants (tomatoes, squash, apple trees, pear trees, and berries) are acceptable for growing in potentially contaminated soil because of the low uptake rate of contaminants into fruits (McBride 2013). Another management strategy for soils with heavy metal contaminants is the addition of amendments. Amendments can dilute the contaminant levels in soils. An individual can immobilize lead in soil as long as the proper amendments are combined with the soil in necessary amounts. The following are possible amendments that are commonly used: Triple Super Phosphate, fishbone, Di Ammonium Phosphate, Mono Ammonium Phosphate, composts, and fertilizers. Such practices as maintenance of soil nutrients and pH, phytotechnologies, addition of amendments, and compost improve soil quality. Mulch cover, crop selection, and raised beds aid to prevent or reduce exposure to humans. Moreover, some basic rules like washing hands, leaving dirty shoes and equipment outside, washing and peeling produce would lessen a potential for inhalation or ingestion of contaminated soil particles.

18.4.3 AIS of Environmental Assessment, Monitoring, and Management of Urban Soils

The system of differentiated indicators and standards of urban soil quality, presented in Smagin et al. (2006) and Korchagina et al. (2014) (Sect. 18.3.1), was the basis for a pilot version of the automated intellectual system (AIS) of the municipal level for the environmental assessment, inventory, and selection of remediation technologies and reproduction (Smagin 2000). The initial data for AIS were taken from the soil survey results that were based on the aforementioned indicators of ecological status.

The input data contain quantitative information of a total land area, portions of open and sealed surfaces, and the GPS coordinates that are used for sampling certain functional elements. These data also include types of soils with their taxonomic names and portions of the total area, sanitary-hygienic, radioactive and toxicological indicators from a surface. Also included are the index bacteria of colon bacillus, the index of enterococcus, pathogenic bacteria, including salmonella, helminth's eggs, petroleum products content and 3.4-benzpyrene, background radiation, and littering. Moreover, horizon-based soil characteristics include (within 1 m) grain-size composition (texture), density of soil, pH, conductivity of a saturated solution, total organic carbon content, mineral nitrogen, mobile phosphorus, and potassium, as well as a total content of heavy metals and metalloids (1, 2 hazard classes: Pb, Cd, Hg, Zn, As). In addition to the analytical data, the survey results contain necessary land cadastral and address information of a site, survey dates, and contact information of the organization that has carried out the research. A survey sheet duplicates as an AIS interface for input of primary information, its subsequent processing and storage in the database of the urban soil sites register.

After characterization of each soil plot, an integrated assessment of the status of soil resources is performed taking into account the percentage of an individual soil type. If any soil issue is identified, AIS provides a portion of the land that the soil is located on and the GPS coordinates of sampling points. The following is also analyzed: the risk of radioactive contamination, general sanitary-epidemiological status, level of site pollution, threat to public health, dominant type of distribution of pollutants, compaction, salinization of electrolytes, and acidity/alkalinity of a contaminated area. A summary form generalizes characteristics of the resource according to its beneficial and harmful substances. A number of integrated indicators of the area are also calculated such as the potential for a site to have bioresources, a deficiency of biophilic elements, an integrated pollution index, an indicator of "ecological balance," or a degree of risk for marginal environments (Smagin et al. 2008).

To adapt *management decisions* for a certain site, an automated selection of technology from an address database is used. The database consists of methods of processing and reclaiming urban soils. Technological recommendations include remediation technologies, soil reproduction, and preventive approaches. Selection depends on a detected soil problem using encoding technology. In an automatic mode, an estimated cost is assessed on the basis of adaption of a certain technology with a price per unit area (weight of soil) and an area of a site with an identified problem. Considering the concept of ecological services, observations from AIS testing of Moscow city functional zones show that compensation of anthropogenic impact on urban soils and restoration costs should be around 20–300 €/ha. This cost is applicable for soils with shortages of elements, compaction, salinization, acidity/alkalinity issues, and pathogenic contamination. A cost of 500–1500 €/ha and above should be applied to soils with heavy metal and metalloid contamination, 3,4-benzpyrene spill, and those that must be exported to local landfills (Smagin et al. 2008).

18.4.4 Sustainable Soil Constructions for Urban Ecosystems

Constructing urban soils is a novel direction in engineering ecology, soil science, and urban management. It aims to develop a scientific background for design and construction of soil layers, phases, fluxes, and barriers to optimize features, regimes, and functions of urban soils (Smagin 2012). Materials used for soil construction are very variable including natural and modified organic and organomineral substances (peat and peat-based modifiers, composts, sewage sludge, humates, and zeolitic complexes), synthetic and polymer hydrogels, films, hydrophobic silicone resins, geotextile, plastic, and gabion items for soil-reclamation and geo-stabilization constructions. Literature review by Smagin and Sadovnikova (2015) provides the following categories of urban soil constructions:

- Artificial agricultural soils (ancient irrigated accumulative soil of river valleys, paddy soils, polders, Chinese piled-up soils "heylutu," "plaggen" soils in Northern Europe, horticultural soils, and dried-out peat lands;
- Soil constructions for sport games (football and rugby fields, tennis courts, golf courses, and race tracks); technical and geo-stabilization constructions (stone gabions, geo- and bio-textiles, bio-mats, geo-nets, and grades);
- Special isolating constructions (geo-membrane, protective screens, artificial geochemical barriers, etc.);
- Technical soil-reclamation constructions (drainage systems, terraces, dams and dikes, cascades, etc.);
- Constructions for water accumulation and salt-protection in arid landscapes and urban areas.

Urban constructions, implemented in urban greenery can give continuous surfaces (urban lawns) or discrete surfaces (constructions under trees and shrubs). Urban soil constructing is based on the artificial development of soil layers' series, simulating natural soil horizons and profiles. Each layer performs specific functions, including accumulation of bioresources or soil protection. The layers are created using organic soil modifiers, based on natural or synthetic biopolymers, together with the local grounds of different texture and dispersity (sands, loams, and clays). Root surface zone includes one or two layers, accumulating nutrients and moisture.

Both natural and synthetic materials (peat, hydrogels, and bio-polymers) mixed with local grounds are used for this purpose. Subsoil is likely separated from the topsoil by a "shield" from coarse-dispersion materials. This breaks off the capillaries, allowing for additional water "hanging" and storage, as well as for preventing from migration of salts and pollutants from the lower layers. Soil constructions' parameters (i.e., depth and sequences of soil layers and material for layer's construction) are estimated based on the fundamental laws of soil physics and models of energy and mass transfer, simulating soils as dynamic multiphase systems (Smagin 2003, 2012; Šimůnek et al. 1998, 2006). Technological projecting of urban soil's constructions implementing computer models of energy and mass transfer (i.e., HYDRUS model, Šimůnek et al. 1998, 2006) is presented in Fig. 18.10. Several scenarios of soil water distribution and water accumulation by the specific plant species are simulated for the initial conditions of the model soil constructions and after implementing specific soil modifiers. One or several accumulative layers at different depths are projected. Model results show that including accumulative layers based on the 0.2% synthetic hydrogels and "AridGrow" soil modifier enables substantial (from 5% to 20–80%) increasing of soil moisture in the root zone of the urban soil construction. This effect remains not only for the gravity water, but also when 3–4 mm/ day water uptake by urban lawns is considered. This increase in water holding and water accumulation capacity expands the period of non-deficit root water consumption (a period, when additional watering is not necessary) on 10–15 days (for the sandy substrates) to 30 days (one accumulative layer at the 10 cm depth) or 40 days (two accumulative layers at the 10 cm depth) (Fig. 18.10d, vertical dotted arrows). Water consumption of 2 mm/day represents critical conditions of lawns' wilting. HYDRUS-1D model results were validated by laboratory experiments on the small simulators of urban soil constructions, and high modeling accuracy was showed (Fig. 18.10a) (Smagin 2012). The developed water-accumulated and salt-protected soil constructions were tested afterwards for irrigation agriculture in arid climates in Persian Gulf countries and for urban environment of Moscow megapolis. Both experiments confirmed high effectiveness of the developed soil constructions (Smagin 2006, 2012; Smagin et al. 2005; Smagin and Sadovnikova 2015).

Another example can be given by soil constructions under green lawns at the municipal greenery experimental station in Dubai. The tested soil constructions included peat-based soil modifier and swelling polymer hydrogel. This novel technology resulted in 2–2.5 time increase of green-lawn biomass (*Paspalum hybrid*)

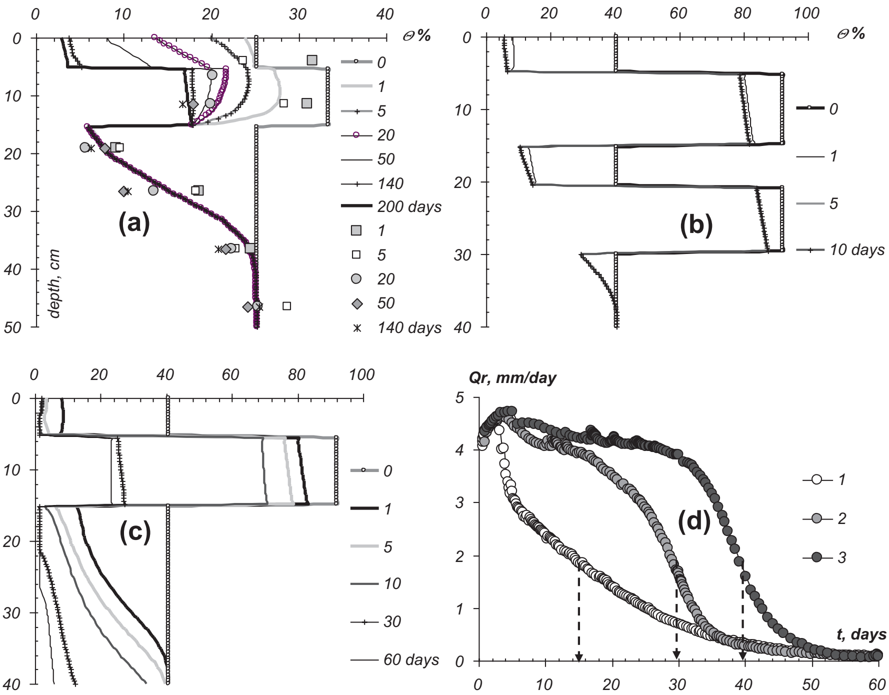


Fig. 18.10 Technological modeling of the layered water_accumulative soil constructions with the crushed_stone screen with the use of HYDRUS-1D software: Θ—volumetric water content (the regime of free gravitational water outflow after saturation): (**a**) construction with a 10 cm thick accumulative layer of 0.2% synthetic swellable hydrogel (experimental data are given by symbols), (**b**) construction with two layers of the peat–sapropel soil modifier, (**c**) the same for the regime of water uptake by the roots of lawn grasses, (**d**) dynamics of water expenditure for transpiration (*Qr*, mm/day) with arrows indicating critical water consumption upon irreversible wilting of the grasses for (1) sand, (2) one layer of the peat–sapropel modifier, and (3) two layers of the peat–sapropel modifier

and improvement of the lawn quality estimated the chlorophyll content (Fig. 18.11a, c). The implemented technology allowed minimizing soil water losses on 30–50% and prevented secondary salinization. Monitoring salt regime based on Ec measuring in soil pastes showed clear tendency to desalinization of the top 30 cm of the soil constructions in first 3 month of the experiment (Fig. 18.11e).

The developed soil constructions have a huge potential for implementation in urban greenery as an alternative of the conventional technologies based on permanent adding of organic substrates to soil surface, since the low effectiveness and high costs of the latter ones were proven by some research (Smagin 2006, 2012; Vasenev et al. 2014a, 2015). Green lawns, glower beds along the roads, in house courts, and in public places provide the niche and the market for implementing technologies of soil construction. Developed constructions shall be sustainable

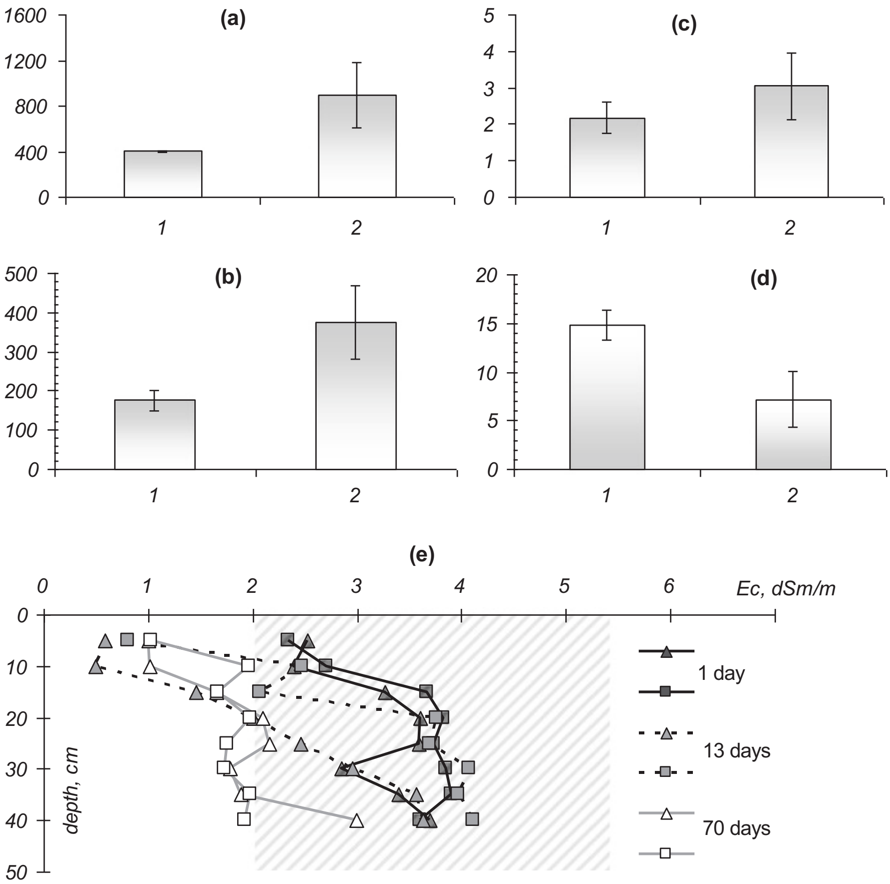


Fig. 18.11 Experimental results of growing green lawns at the station of landscape and gardening of Dubai: fresh phytomass (g/m^2) (**a**); absolutely dry phytomass (g/m^2) (**b**); chlorophyll content (mg/g) (**c**); irrigation water (l/m^2 day) (**d**); electric conductivity (Ec) of soil pores solutions (**e**). Experimental sites include control (1) and developed soil construction (2). Triangles show SPH treatments, squares show low-moor peat treatment, and hatching signifies salinization zones

to bioclimatic conditions and anthropogenic pressures (i.e., salinization and contamination). They shall provide key functions for urban vegetation, including nutrient, water, and heat accumulation. Specific features and high heterogeneity of urban soils will require for additional experiments to adapt technologies of soils' constructions to urban environments. However, successful experience obtained in different climates and managements types assures the possibility of such adaptation and affirms substantial increase of soil quality and in result. For example, implementing these constructions in specific arid conditions allowed to saving half of watering expenditures, which was a limiting factor for agricultural development at the deserted areas.

18.4.5 Conclusion

Although urbanization is increasingly important, its environmental consequences for soils' functions and quality are still poorly known. Urban soil is a very complicated object to study, access, and manage. Urban soils provide multiple functions and are exposed to numerous threats. Anthropogenic factor dominates formation and functioning of urban soils, contributing to their heterogeneity. High spatial variability and temporal dynamics of urban soils' features and functions require for advanced approaches to monitor, access, and manage their quality.

In the current chapter we reviewed the key soil functions proposed by European, American, and Russian classifications and analyzed their performance for the specific case of urban soils. Different methods and indicators to monitor and assess urban soils' quality were discussed, including chemical and microbiological indexes, soil regimes and supply of nutrients, water, and contaminants. We proved that conventional methods based on agricultural or sanitary parameters underestimate urban soil's quality. Only an integral complex assessment, incorporating static and dynamic parameters, physical, chemical, and biological features, bioclimatic and economic indexes, can give an adequate value to the role, which urban soils play for environment and society. Different methods and implementations of the integral assessment of urban soils' quality were described for the case studies for the megapolises with different climatic, economic, and historical conditions, e.g., Moscow, New York, and Dubai.

Relevant assessments of urban soils' functions and quality provide the basic information for a proper management of urban soils and urban ecosystems. We demonstrated that urban soil's management, including recommendations for gardeners, best management practices, automated intellectual systems, and urban soils' constructions, are much more efficient when the multiple functions, which they perform, are considered.

Urban soils are the most dependent on the anthropogenic factor. They are altered or artificially created by humans and for humans. Smart management of urban soil's quality can substantially increase functions and services of urban soils, whereas extensive and thoughtless use can result to their degrading. Management practices, currently implemented for urban sols in the major large cities, are still rather far from being sustainable, therefore maintaining urban soils' quality remains an important issue. The problems highlighted and the solutions proposed in the chapter contribute to development of the smart management practices for urban soils' functions and quality, which is an integral component of the sustainable cities of the future.

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Part III

Regional and Global Initiatives for Soil Resource Management

Enhancing Resource Use Efficiency Through Soil Management for Improving Livelihoods

19

Suhas P. Wani, Girish Chander, and K.H. Anantha

Abstract

Sustainable intensification and improvement in farm-based livelihoods particularly in dryland tropics are the biggest challenges of the century. Widespread soil degradation, growing water scarcity, and looming threat of climate change further compound the problem of achieving food and nutritional security along with improved livelihoods. Large yield gaps in drylands provide a huge opportunity to increase the food production for future food security and mainstreaming of drylands. Soil management for correcting micro and secondary nutrient deficiencies has shown to increase crop productivity by 20–66% in Karnataka, India. During 2009–2013 in this state, more than 5 million farmers benefitted and net economic benefits through increased production were estimated to the tune of US$353 million (Rs. 1963 crores). Balanced nutrition led to increased nitrogen uptake efficiency, utilization efficiency, and use efficiency for grain yield and harvest index. Best practices like soil test-based fertilization including micronutrients and improved cultivars also contribute to increasing rainwater use efficiency in crops by channelizing unproductive evaporation loss into productive transpiration. In current rainy fallow regions, the landform management like broadbed and furrow along with balanced nutrition has shown that fallow lands in black soil regions in Madhya Pradesh can be successfully cultivated to grow soybean crop. Similarly soil fertility management along with other best practices provides opportunities for intensification through cultivating 11.4 million ha rice fallow in India by growing of early maturing chickpea. Thus, efficient rainy and post-rice fallow management is a way forward to enhance land

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use efficiency for higher productivity and incomes. Along with productivity and economic benefits, improved soil-nutrient-crop-water management is found to contribute to organic C building, enhancing microbial activity and resilience building of production systems. Efficient soil management thus serves as a foundation to enhance livelihoods through resource-efficient production and providing opportunities for scaling up.

Keywords
Agriculture • Incomes • Nutrient use efficiency • Soil degradation • Water use efficiency

19.1 Resource Crunch and Future Food Security: A Daunting Challenge

The biggest challenge of the 21st century is to ensure food security and reducing poverty with finite and scarce land and water resources for the ever growing global population expected to reach 9 billion+ by 2050 from 6.5 billion today (Wani et al. 2009b). Most of this increase in population is expected to occur in less-developed countries in Asia and Africa, where most of the poor live and where rainfed agriculture forms the dominant basis for livelihood security (Singh et al. 2009). Current global food production comes from 1.5 billion ha of cultivated land, representing 12% of the total land area (Schultz and de Wrachien 2002; Hanjra and Qureshi 2010). About 1.1 billion ha (80% of world's physical agricultural area) is rainfed and generates about 60% of the world's staple food (Hanjra and Qureshi 2010). Irrigated agriculture covers only 279 million ha or 19% of cropland (Thenkabail et al. 2010) (it becomes 400 million ha when multiple crops/cropping intensity is considered), but contributes 40% of agricultural output. In the last few decades the emerging evidence indicates that crop productivity growth in irrigated areas has slowed or stagnated due to multiple factors. Relying on irrigated agriculture is not possible as data on water supply and demand are startling: about 450 million people in 29 countries face severe water shortages (Serageldin 2001); as much as two-thirds of the world population could be water-stressed by 2025 (Seckler et al. 1999); aquifers, which supply one-third of the world's population, are being pumped out faster than nature can replenish them (Shah et al. 2006); half of the world's rivers and lakes are polluted; and major rivers, such as the Yellow, Ganges, and Colorado, do not flow to the sea for much of the year because of upstream withdrawals (Richter et al. 2003). In the current scenario, the potential of rainfed agriculture is well recognized, and therefore the increased food production has to come from land and water resources which are finite and in a degrading state (Wani et al. 2011a). The farm productivity and resource use efficiency in rainfed and irrigated agriculture are declining over the years due to inappropriate water and land management practices, water scarcity, and land degradation, and climate change is posing further challenges. The current water use efficiency in rainfed agriculture varies from 35 to 45%, and huge amount of fresh water harvesting, as soil moisture during monsoon period is lost through the nonproductive evaporation resulting in poor water use efficiency.

In India, population is expected to increase from the current 1.21 billion in 2011 (Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India 2014) to the expected 1.69 billion by 2050 (FAOSTAT 2013). Within existing land and water constraints, India must sustainably increase the productivity levels of the major rainfed crops to meet the ever-increasing demand of food to around 380 million tons in 2050 (Amarasinghe et al. 2007). Nearly 55% of the population in India is dependent on agriculture and allied sectors for their livelihoods, and agriculture contributes only around 14% to the nation's gross domestic production (GDP) (Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India 2014). The total cultivable land in India is 141 million ha with a cropping intensity of 135%. Indian agriculture is essentially small farm agriculture with majority of farmers' owning less than 1 ha of land, and 83% of farmers represent small farming households (Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India 2014). Groundwater and surface water sources in India irrigate about 44 and 21 million ha of agricultural lands, respectively, (nearly 46% of total cultivable land) and rest of the cultivable area (76 million ha) is rainfed. In India, per capita water availability has declined from 5177 m^3 in 1951 to 1545 m^3 in 2011 due to the rise in population from 361 million in 1951 to 1.21 billion in 2011 (Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India 2014). Water resources in most of the river basins have been allocated and/or utilized among various sectors (domestic, agriculture, industry, energy, ecosystems, etc.) and only limited scope exists to further harvest the fresh water. The irrigated regions are at or near to productivity plateau and there is little scope to increase the food production. Thus, rainfed regions which are bypassed for development in the past are at center stage for enhancing food production, while sustaining it in irrigated regions.

19.2 Fatigue in Food Production in Irrigated Regions and Rainfed Regions: Hope for Food Security

The farm productivity and resource use efficiency in both irrigated and rainfed systems are declining over the years due to inappropriate water and land management practices, water scarcity, land degradation, land fragmentation, lack of access to credit and markets, etc. Further, the climate change has led to the vulnerability of food production in tropical countries like India (Boomiraj et al. 2010; Rao et al. 2013). Despite huge investments (approx. 60 billion USD), the area under irrigation is not increasing and at the same time yields are stagnating (Shah 2011). Therefore, future food security largely depends on the rainfed systems, as current farmers' yields are lower by two to five folds than the achievable potential yields (Rockström et al. 2007; Wani et al. 2009b).

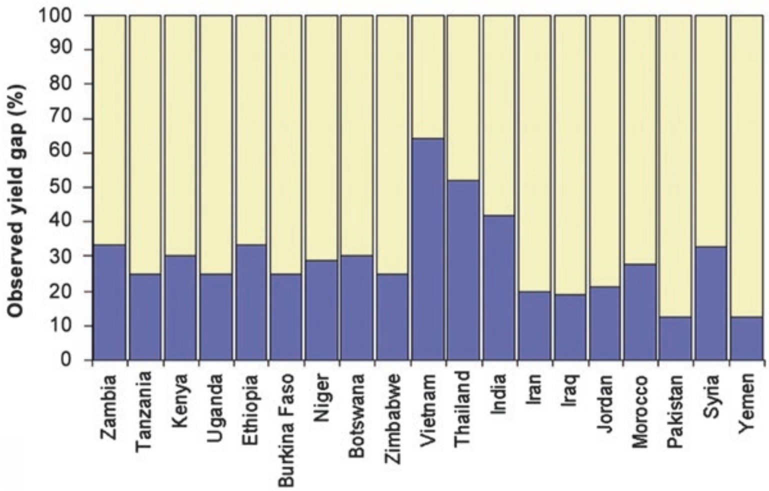

Fig. 19.1 Observed yield gaps (for major grains) between farmers' yields and achievable yields (100% denotes achievable yield level and columns actual observed yield levels). Source: Rockström et al. (2007)

19.3 Crop Yield Gaps and Opportunities

The actual yields from rainfed agriculture are quite low, as compared to achievable ones in semiarid tropical agro-ecosystems (Wani et al. 2012c). In countries in Eastern and Southern Africa the yield gap is very large. In many countries in West Asia, farmers' yields are less than 30% of achievable yields, while in some Asian countries the figure is close to 50%. Historic trends present a growing yield gap between farmers' practice and farming systems that benefit from management advances. The existing large yield gaps between the current and the potentially achievable crop yields particularly in the rainfed areas provide a huge opportunity to increase the country's food production substantially (Fig. 19.1).

Long-term studies at ICRISAT show that it is possible to achieve grain productivity of 5.1 tons per ha from rainfed agriculture compared to 1.1 tons per ha currently being achieved (Wani et al. 2003a, 2012c). Both management practices are sustainable in the long run, but have different carrying capacities, farmers' practice having a low carrying capacity of 5 persons ha^{-1}, while improved management 27 persons ha^{-1}, which is urgently needed for feeding the burgeoning population. The study validated the need for knowledge-based management in the drylands to bridge yield gap for future food security and improved farm incomes and livelihoods for smallholders in the SAT (Fig. 19.2).

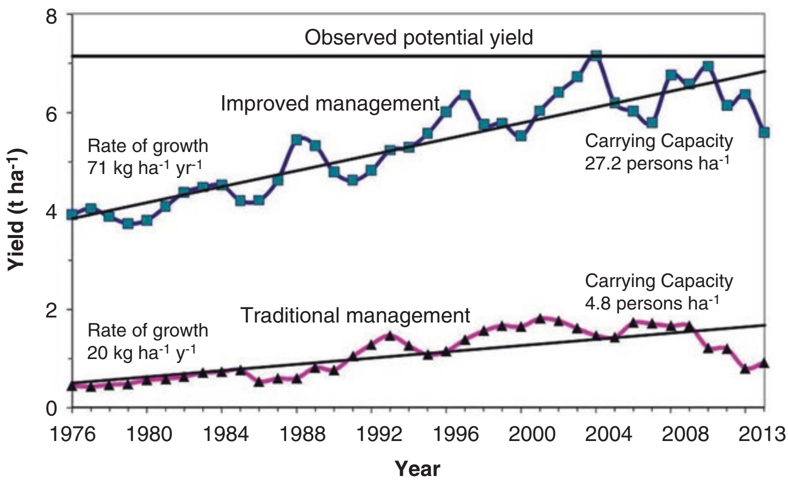

Fig. 19.2 Crop yields under improved and traditional management systems during 1976–2013 at ICRISAT, Patancheru, India

19.4 Issues with Regard to Soil Management

19.4.1 Poor Soil Health and Soil Degradation

Studies show that multi-nutrient deficiencies are constraining farmers from achieving the potential yields (Table 19.1). Soil analysis results from farmers' fields in different states like Andhra Pradesh, Gujarat, Karnataka, Kerala, Madhya Pradesh, Rajasthan, Tamil Nadu, Gujarat, and Jharkhand showed widespread deficiencies (18–100%) of secondary nutrients like sulfur and micronutrients like zinc, boron which have emerged as main constraints for sustaining agricultural productivity (Wani et al. 2012a, 2011b, 2013, 2015a, b; Sahrawat et al. 2010, 2007; Rego et al. 2005; Chennamaneni et al. 2014; Chander et al. 2012, 2013a, b, 2014b). The traditional practice of applying farm yard manure (FYM) has also declined as chemical fertilizers, like urea, are cheaper. Organic manure is used only for high-value crops. Soil organic carbon and nitrogen are primary indicators of soil health. Most of the arable land, across the country, shows low levels of soil organic carbon with deficiencies ranging from 11% to 76% (Wani et al. 2015a). Similarly, soils suffer from deficiencies of phosphorus 21–74% while potassium deficiencies (1–24%) are not really limiting factor. The secondary and micronutrient deficiencies across the states ranged between 46–96% for sulfur; 56–100% for boron; and 18–85% for zinc. The general practice by the farmers is to add fertilizers containing only macronutrients [nitrogen–phosphorus–potassium (NPK)] and are not aware of secondary and micronutrient deficiencies which are apparently acting as limiting factors for the food production.

Table 19.1 Percent of farm field soil samples found deficient in available nutrients and having low levels of soil organic C

State	% samples with low levels of soil organic C	% samples deficient in available nutrients				
		P	K	S	B	Zn
Andhra Pradesh	76	38	12	79	85	69
Gujarat	12	60	10	46	100	85
Karnataka	52	41	23	52	62	55
Kerala	11	21	7	96	100	18
Madhya Pradesh	22	74	1	74	79	66
Rajasthan	38	45	15	71	56	46
Tamil Nadu	57	51	24	71	89	61

Source: Wani et al. (2015a)

19.4.2 Imbalanced Use of Fertilizers

The past fertilizer application strategies have resulted in more application of nitrogen and phosphorous containing fertilizers, which is currently in the NPK ratio of 8:2.7:1 instead of desired 4:2:1 (Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India 2014). Imbalanced use of fertilizers arises due to (1) fertilizer subsidy of the government skews the fertilizer consumption pattern in the country, (2) inadequate availability of the required fertilizers at the stipulated time in rural areas, and (3) lack of knowledge among farmers as to what nutrients are required by the crops and what is missing from their lands. For inputs such as improved cultivars, seeds, and pesticides, private companies and their dealer networks provide the information to the farmers. However, there is a limited or, in some cases, no such practice existing for fertilizers. The public infrastructure for soil analysis is poorly developed. Farmers rarely get the information in time, and these laboratories often provide information on NPK fertilizers in a format that farmers fail to understand.

Fallout of the fertilizer subsidy is that chemical fertilizers are cheaper than organic fertilizers. Thus, farmers have moved away from using organic manure, which is very critical for preserving good soil health, as organic carbon is the key fuel for keeping the soil microbial activities in a good state. Good soil health is required to ensure the quality of food, and for food and nutritional security. To address malnutrition in India, it is more economical and efficient to address food quality issues through soil health and diet diversification rather than through biofortification and nutritional amendments externally.

Unbalanced use of fertilizers also leads to depletion of particular nutrients in the soils as well as causing environmental degradation. It increases the cost of cultivation and also lowers its efficiency.

19.4.3 Declining Efficiency of Fertilizer Use

Subsidies and increased awareness about fertilizers have led to a significant increase in fertilizer consumption (Table 19.2). More importantly, while fertilizer

Table 19.2 All India consumption of N, P, and K fertilizers and area and production of food grains

Year	Consumption (000 t)			Total NPK (000 t)	Area (million ha)	Production (million t)	Fertilizer use efficiency (kg food per kg NPK)
	N	P	K				
1950–1951	58.7	6.9		65.6	97.3	50.8	775
1955–1956	107.5	13.0	10.3	130.8	110.6	66.9	511
1960–1961	210.0	53.1	29.0	292.1	115.6	82.0	281
1965–1966	574.8	132.5	77.3	784.6	115.1	72.4	92.2
1970–1971	1487.0	462.0	228.0	2177.0	124.3	108.4	49.8
1975–1976	2148.6	466.8	278.3	2893.7	128.2	121.0	41.8
1980–1981	3678.1	1213.6	623.9	5515.6	126.7	129.6	23.5
1985–1986	5660.8	2005.2	808.1	8474.1	128.0	150.4	17.8
1986–1987	5716.0	2078.9	850.0	8644.9	127.2	143.2	16.6
1987–1988	5716.8	2187.0	880.5	8784.3	119.7	140.4	16.0
1988–1989	7251.0	2720.7	1068.3	11040.0	127.7	169.9	15.4
1989–1990	7386.0	3014.2	1168.0	11568.2	126.8	171.0	14.8
1990–1991	7997.2	3221.0	1328.0	12546.2	127.8	176.4	14.1
1991–1992	8046.3	3321.2	1360.5	12728.0	121.9	168.4	13.2
1992–1993	8426.8	2843.8	883.9	12154.5	123.2	179.5	14.8
1993–1994	8788.3	2669.3	908.4	12366.0	122.8	184.3	14.9
1994–1995	9507.1	2931.7	1124.7	13563.5	123.9	191.5	14.1
1995–1996	9822.8	2897.5	1155.8	13876.1	121.0	180.4	13.0
1996–1997	10301.8	2976.8	1029.6	14308.2	123.6	199.3	13.9
1997–1998	10901.8	3913.6	1372.5	16187.9	124.1	192.3	11.9
1998–1999	11353.8	4112.2	1331.5	16797.5	125.2	203.6	12.1
1999–1900	11592.7	4798.3	1678.7	18069.7	123.1	209.8	11.6
2000–2001	10920.2	4214.6	1567.5	16702.3	121.1	196.8	11.8
2001–2002	11310.2	4382.4	1667.1	17359.7	122.8	212.9	12.3
2002–2003	10474.1	4018.8	1601.2	16094.1	113.9	174.8	10.9
2003–2004	11077.0	4124.3	1597.9	16799.2	123.5	213.2	12.7
2004–2005	11713.9	4623.8	2060.6	18398.3	120.1	198.4	10.8
2005–2006	12723.3	5203.7	2413.5	20340.5	121.6	208.6	10.3
2006–2007	13772.9	5543.3	2334.8	21651.0	123.7	217.3	10.0
2007–2008	14419.1	5514.7	2636.3	22570.1	124.1	230.8	10.2
2008–2009	15090.5	6506.2	3312.6	24909.3	122.8	234.5	9.4
2009–2010	15580.0	7274.0	3632.4	26486.4	121.3	218.1	8.2
2010–2011	16558.2	8049.7	3514.3	28122.2	126.7	244.5	8.7
2011–2012	17300.3	7914.3	2575.4	27790.0	124.8	259.3	9.3
2012–2013	16820.9	6653.4	2061.8	25536.1	120.8	257.1	10.1
2013–2014	16750.1	5633.5	2098.9	24482.5	126.0	264.8	10.8

Source: Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India (2014) consumption continued to rise substantially, the elasticity of output with respect to fertilizer use has dropped sharply. During the period since 1970–1971 to 2010–2011, while food grain production grew by about 2.3 times (108.4–244.5 million ton), the increase in fertilizer (NPK) consumption (2177–28122.2 thousand ton) was about 13 times (Directorate of Economics & Statistics, Department of Agriculture & Cooperation, Ministry of Agriculture, Government of India 2014). However, the trends now show positive signs with food production at 264.8 million ton with use of 24482.5 thousand ton NPK fertilizers during 2013–2014. The average crop response was about 50 kg of food grain per kg of NPK fertilizer during the 1970–1971, and fell to about 8.70 during 2010–2011 and about 10.8 during 2013–2014. The increase in fertilizer use has come at significant cost. The fiscal burden of fertilizer subsidy was Rs. 60 crore in 1976–1977, which shot up to over Rs. 70,000 crore in 2012–2013. There are other important costs in the form of long-term soil degradation, degradation of water resources (in both quantity and quality), and general stagnation of yields due to application of suboptimal nutrient ratios.

Thus, disproportionate NPK fertilizer application, multinutrient deficiencies, and lack of organic manure application have led to reduction in the carbon content of the soil and contributed to stagnating agricultural productivity.

19.5 Soil Management as an Entry Point Activity

Entry point activity (EPA) in any project involves building the rapport with the community, strengthening, and sustaining it throughout the project and beyond. Selection of the appropriate EPA for building rapport with the community is very critical and an ideal EPA must have the following elements (Wani et al. 2009a):

- EPA should be knowledge based and should not involve direct cash payment through the project in the village.
- An activity should have a high success probability (>80–90%) and be based on proven research results.
- The EPA should involve participatory research and development (PR&D) approach, and community members should preferably be involved in undertaking the activity in watersheds.
- An EPA should result in the measurable tangible economic benefits to the farming community with a relatively high benefit:cost (B:C) ratio.
- The EPA preferably should be simple and easy for the participating farmers to undertake its participatory evaluation.
- Most importantly, the EPA should benefit the majority of farmers in the watershed; and
- Should have a reliable and cost-effective approach to assess the constraints.

Knowledge-based entry point interventions like soil mapping targeted at providing simple solutions to widespread problems are the best options for quick benefits and rapport building with the majority of farmers to initiate a collective action for technological upgradation of dryland agriculture (Wani et al. 2009a; Dixit et al. 2007; Chander et al. 2016). The characterization of fertility status of farmers' fields particularly in India has indicated micro and secondary nutrient deficiencies of boron (B), zinc (Zn), and sulfur (S) in addition to nitrogen (N), phosphorus (P), and potassium (K) (Wani et al. 2002a, b, 2009a, 2011b, 2012a, 2013, 2015a, b; Sahrawat et al. 2007, 2010; Chander et al. 2012, 2013a,b, 2014a,b). Such nutrient depletion is the chief biophysical factor limiting production. Soil health is prerequisite to strengthen agri-based enterprises and therefore has proved to be a very effective entry point intervention to quickly harness the productivity benefits while bringing on board the majority farmers to initiate the process of upgradation of dryland agriculture.

19.6 Soil Management at Watershed Catchment Scale for Enhanced Productivity and Resource Use Efficiency

Development at watershed catchment scale is one of the most trusted and eco-friendly approaches to managing soil and water resources and is capable of addressing many natural, social, and environmental intricacies (Rockström et al. 2007; Samra 1998; Wani et al. 2002b, 2003a, b). Management of natural resources at the watershed scale produces multiple benefits in terms of increasing food production, improving livelihoods, protecting the environment, addressing gender, and equity issues along with biodiversity concerns (Ahluwalia 2005; Rockström et al. 2007; Wani et al. 2003a, b, 2009a), and is also recommended as the best option to upgrade rainfed agriculture to meet the growing food demand globally (Rockström et al. 2007; Wani et al. 2007).

Soil test-based balanced nutrient management (application of deficient SBZn along with NP) as an EPA in fields in watersheds recorded 70–119% (2100 kg ha^{-1} in maize, 660 kg ha^{-1} in groundnut, 640 kg ha^{-1} in mungbean, and 1070 kg ha^{-1} in sorghum) improvement in crop productivity along with additional returns varying from Rs. 16,050/- to 28,160/- ha^{-1} over the farmers' practice (only NP) (Wani et al. 2014, 2016). Improved nutrient management recorded favorable benefit-cost ratios (1.43–15.2) over the farmers' practice (Wani et al. 2016).

Improved watershed management by the way of constructing water harvesting structures, cultivation across the slope, planting of *Gliricidia* on the bunds, less-exposed soil due to increased cropping intensity, increased use of organic manures, and better crop growth due to adoption of balanced nutrition and other best practices results in restriction to free flow of water leading to more infiltration and thereby reduced runoff in comparison to the rainfall received (Wani et al. 2012c). The reduced runoff which infiltrates into the soil apparently strengthens the green water sources in rainfed agriculture, the consumption of which is almost threefold more than blue water consumed (5000 vs. 1800 km^3 year^{-1}) for food production (Karlberg et al. 2009). The impact of soil management for conserving in situ and ex situ moisture in watershed interventions is recorded as improvement in the groundwater. As a result of watershed interventions, the water use efficiency by different crops increases with substantial productivity improvement (Wani et al. 2012c), resulting in higher profit margin. Increased water availability enables farmers to increase cropping intensity and diversify to more remunerative land use systems involving horticulture, forage production on sloping lands, etc. Forage promotion strengthens livestock-based livelihoods which provide an alternative source of income and livelihoods, in addition to improving resilience to shocks. Soil erosion, which is a major environmental problem particularly in South Asia (Barton et al. 2004) and other parts of the SAT, is decreased due to improved watershed measures which apparently restrict displacement of soil particles and loss with the reduced runoff water.

Landform management to alleviate waterlogging proved effective intervention to manage high clay Vertisols for higher soybean and groundnut productivity by 13–27% (340–350 kg ha^{-1} in soybean and 160–250 kg ha^{-1} in groundnut) over the farmers' practice (Wani et al. 2014). However, the integrated approach of balanced nutrition and landform management plus improved cultivar was the best option in increasing sunflower productivity by 182% (1600 kg ha^{-1} in sunflower) over farmers' management (control). Adoption of soil-water-crop interventions in target watersheds has shown to abridge yield gaps by 12–96% in groundnut (160–1280 kg ha^{-1}), 29–100% (240–1130 kg ha^{-1}) in pigeonpea, and 0–100% (0–1175 kg ha^{-1}) in chickpea.

The findings from the watershed site at Kothapally revealed that watershed interventions increased the resilience of the production systems and thereby ensured the income stability during adverse climatic conditions (Wani et al. 2012c, 2009b). During the drought year 2002, crop productivity and average incomes from the watershed area were far larger compared to the non-watershed area and farmers in treated watershed area could meet their livelihood in the village, whereas in untreated village a steep decline (44–12%) in the share of agricultural income in total income indicated that people relied on increased nonagricultural sources of income, i.e., through migration during the drought year.

19.7 Soil Health Management for Farm-Based Livelihoods: Case of Bhuchetana in Andhra Pradesh

Under the Bhuchetana initiatives in Andhra Pradesh, the soil health mapping was undertaken in pilots across districts of Andhra Pradesh state which showed widespread soil fertility degradation. New fertilizer management strategies were designed which also included deficient sulfur, boron, and zinc in addition to nitrogen, phosphorus, and potassium. Along with department of agriculture, the balanced fertilizer management was scaled out in farmers' fields. The crop cutting experiments with all major crops during 2011–2012 to 2013–2014 showed significant productivity benefits between 20 and 50% (Fig. 19.3; Table 19.3). In economic terms, one rupee spent on soil management resulted benefit of Rs. 3/- to 15/- through higher crop productivity.

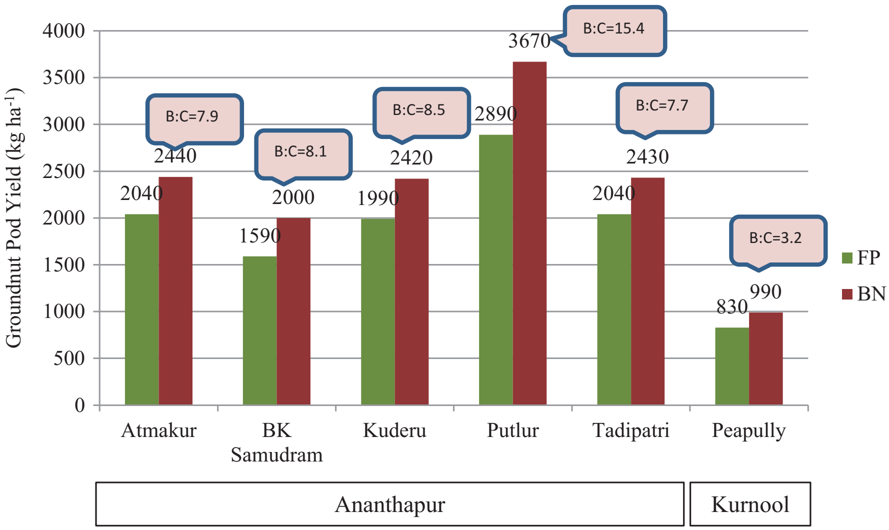

Fig. 19.3 Effects of balanced nutrition on groundnut pod yield in Anantapur and Kurnool districts, Andhra Pradesh, rainy/kharif season 2012

Table 19.3 Effects of soil test-based balanced nutrient management on paddy yield in Andhra Pradesh during post-rainy/rabi 2013–2014 season

District	Mandal	Grain yield			B:C ratio
		FP	BN	% increase	
East Godavari	U Kothapalli	7180	8360	16	11
Guntur	Karempudi	5920	7360	24	13
	Nekarikallu	5160	6440	25	12
	Rompicherla	4600	6170	34	14
Kadapa	Duvvur	5320	6260	18	5
	Khajipeta	5330	6550	23	7
Krishna	Gudlavalleru	4830	7150	48	13
	Kalidindi	4740	5770	22	6
Prakasam	Kandukoor	3300	3910	18	6
	Maddipadu	3820	5170	35	12
	Ongole	4220	5210	23	9
	Singarayakonda	4780	6040	26	12
Srikakulam	Rajam	6000	7370	23	13
Vijayanagaram	Gajapathinagaram	4540	5490	21	9

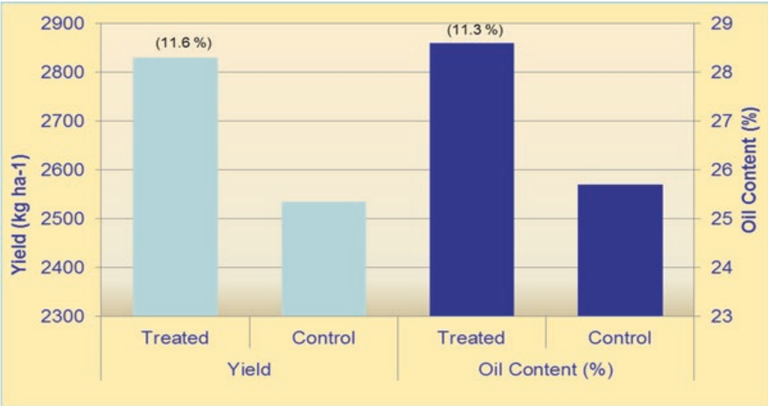

Fig. 19.4 Effects of balanced nutrient management on sunflower yield and oil content in Kadapa, post-rainy/rabi 2011–2012

Along with productivity and economic benefits, crop quality like oil content in sunflower also improved (Fig. 19.4). In our efforts to linking farmers with the markets, it is not only the produced quantity that matters, but also the quality. Therefore, science-led soil management strengthens farmers in effectively linking with the markets.

19.8 Scaling Out Soil Management for Improving Livelihoods: Exemplar Case of Bhoochetana in Karnataka

19.8.1 Yield Increase Through Soil Health Rejuvenation

Bhoochetana was implemented strategically on phased manner to make essential gains in the struggle for improved agricultural productivity, rural incomes, and nutrition. The scaling-up process in this particular project adopted a multilevel "refinement strategy" to increase the effectiveness of technologies and reach greater number of people. It is part of a broader process of innovation and learning. With effective monitoring and evaluation processes, the knowledge acquired from the initial year was used to scaling up the model to create larger impacts in the entire state. The process occurred in an iterative and interactive cycle, as the experience from scaling up feeds back into new ideas and learning.

The unique mechanism of scaling up with comprehensive planning, review, and monitoring along with new institutions like Farm Facilitators (FFs), lead farmers, RSKs, and supporting policies enabled the consortium to cover large rainfed areas in the state. The initiative began with six districts with an area of 0.2 million ha covered mostly cereal crops and extended to nearly 5 million ha in the subsequent years covered all major cereals, legumes, and oilseed crops. As the cropping system is diverse, during 2011, the focus was shifted to include even irrigated crops like paddy and sugarcane to realize their potential yield level. Crop cutting experiments data was the base to undertake yield analysis by comparing improved management practices with farmers' own practice. To estimate average values for farmers' practice and improved practice, boxplots were used to identify extreme cases and outliers for the major crops. The average yields of cereal crops in improved practices were higher than in farmers' practice. Maize is grown more extensively in almost all the districts, except coastal areas, had impressive yield benefits during normal rainfall year. However, poor rainfall and soil fertility status reduced grain yield especially during 2011–2012 and 2012–2013 (Table 19.4). Average maize productivity significantly reduced from 5420 to 3700 kg ha^{-1} in 2012 in case of farmers' practice; from 7800 to 4850 kg ha^{-1} in 2012 ($P < 0.01$) with improved practice. As a result, the incremental gain also reduced from 44 to 31% over farmers' practice. The drastic difference is also due to difference in the type of maize hybrids used, plant spacing, and application of supplemental irrigation.

Although, finger millet is considered as drought-tolerant crop, the average productivity declined from 1680 to 1460 kg ha^{-1} ($P < 0.01$) in case of farmers' practice and 2550 to 1870 kg ha^{-1} ($P < 0.01$) with improved practice during 2009 and 2013, respectively. Given the perception that finger millet responded to improved management practices very meagerly, the increased rate of yield in Bhoochetana is significant. The improved practice helped farmers to harness better yield compared to conventional practice despite drought condition. Rabi sorghum (post-monsoon) is grown in considerable area was also registered productivity loss compared to wet year. During normal (2010) and dry (2011) rainfall year, the rabi sorghum yield was highest as it recorded around 1370 and 1960 kg ha^{-1} ($P < 0.01$) and 1450 and 1910 kg ha^{-1} ($P < 0.01$) under farmers' practice and improved practice, respectively. Pearl millet, one of the staple food grains in northern Karnataka, had shown mixed response to water stress situation between 2010 and 2013. Wheat cultivated in few districts showed positive response to improved management practices as increased yield from 610 and 810 kg ha^{-1} in 2012 to 1000 and 1380 kg ha^{-1} in 2013 under farmers' practice and improved practice, respectively.

Similarly, the average grain yields of legumes and oilseed crops also presented in Table 19.5 revealed that the rainfall had major influence on grain yield. The average yield of blackgram was 930 and 1260 kg ha^{-1} in 2010; 670 and 890 kg ha^{-1} in 2011 ($P < 0.05$); 1220 and 1640 kg ha^{-1} in 2012 ($P < 0.01$); 570 and 760 kg ha^{-1} in 2013 ($P < 0.05$) under farmers' practice and improved practice, respectively. Chickpea is a post-monsoon crop which is generally grown with residual soil moisture performed better under improved practice compared to farmers' practice. The average chickpea yield was 1140 and 1470 kg ha^{-1} in 2009; 1380 and 1810 kg ha^{-1} in 2010; 920 and 1210 kg ha^{-1} in 2011; 630 and 820 kg ha^{-1} in 2012; 770 and 1020 kg ha^{-1} in 2013 ($P < 0.01$) under farmers' practice and improved practice, respectively (Table 19.5). The average groundnut yield was ranging between 1300 and 2100 kg ha^{-1} between 2009 and 2013, respectively, under improved practice and 930 and 1500 kg ha^{-1} under farmers' practice during the same period. Similarly, average Soybean yield was ranging between 1060 and 1930 kg ha^{-1} between 2009 and 2013 under farmers' practice and 1400–2620 kg ha^{-1} under improved practice during the same period (Table 19.5). The productivity difference between farmers' practice and improved practice ranged between 30 and 42% with changing rainfall variability.

Table 19.4 Total grain yield (kg ha^{-1}) of cereals, pulses, and oilseed crops under Bhoochetana between 2009–2010 and 2013–2014 in Karnataka

Cereals					Pulses				Oilseeds			
		Yield (kg ha^{-1})				Yield (kg ha^{-1})				Yield (kg ha^{-1})		
Crop year	Crop	FP	IP	LSD	Crop	FP	IP	LSD	Crop	FP	IP	LSD
2009–2010	Maize	5420	7800 (44)	356**	Chickpea	1140	1470 (29)	178**	Groundnut	1080	1490 (39)	122**
	Finger millet	1680	2550 (52)	157**					Kharif Sunflower	810	1120 (38)	188**
	Rabi sorghum	1230	1780 (45)	103**					Soybean	1770	2620 (48)	231**
2010–2011	Kharif sorghum	1710	2300 (35)	387**	Blackgram	930	1260 (36)	424NS	Groundnut	1500	2130 (42)	134**
	Maize	5820	7560 (30)	441**	Greengram	470	660 (42)	122**	Kharif Sunflower	590	720 (21)	280NS
	Pearl millet	1690	2250 (33)	275**	Pigeonpea	1200	1620 (35)	135**	Soybean	1930	2540 (32)	228**
	Finger millet	1910	2620 (37)	112**	Chickpea	1380	1810 (31)	170**				
	Rabi sorghum	1370	1960 (43)	368**								
2011–2012	Kharif sorghum	2080	2910 (40)	428**	Blackgram	670	890 (34)	200*	Groundnut	1160	1610 (39)	291**
	Maize	3900	5110 (31)	440**	Cowpea	270	400 (45)	34**	Kharif Sunflower	1080	1460 (35)	530NS
	Paddy	4340	5120 (18)	325**	Fieldbean	1490	1940 (30)	607NS	Soybean	1480	1990 (35)	213**
	Pearl millet	1830	2540 (39)	459**	Greengram	540	760 (41)	167*	Rabi Safflower	730	960 (31)	133**
	Finger millet	1500	1960 (31)	215**	Pigeonpea	915	1260 (38)	166**	Rabi Sunflower	1420	1970 (38)	737NS
	Rabi sorghum	1450	1910 (32)	268**	Chickpea	920	1210 (32)	145**				

2012–2013	Kharif sorghum	2050	2670 (30)	400**	Blackgram	1220	1640 (35)	128**	Groundnut	930	1220 (31)	140**
	Maize	3700	4850 (31)	437**	Fieldbean	870	1160 (33)	283*	Kharif Sunflower	1010	1320 (31)	232**
	Paddy	3630	4600 (27)	310**	Greengram	840	1110 (33)	125**	Soybean	1060	1400 (33)	409NS
	pearl millet	1300	1790 (38)	253**	Horsegram	100	130 (26)	90NS	Rabi Safflower	510	650 (29)	171NS
	Rabi Maize	2190	3100 (41)	978NS	Pigeonpea	980	1250 (27)	274NS	Rabi Sunflower	720	950 (32)	250NS
	Finger millet	1380	1830 (32)	204**	Chickpea	630	820 (29)	128**				
	Rabi sorghum	1210	1590 (31)	138**								
	Wheat	610	810 (32)	145**								
2013–2014	Kharif sorghum	2110	2770 (31)	352**	Blackgram	570	760 (34)	145*	Groundnut	1310	1700 (30)	126**
	Maize	4100	5340 (30)	220**	Cowpea	320	430 (34)	71**	Kharif Sunflower	1020	1390 (36)	240**
	Paddy	3990	4940 (24)	164**	Fieldbean	640	880 (38)	189*	Soybean	1480	1860 (26)	121**
	Pearl millet	1410	1960 (39)	177**	Greengram	450	590 (30)	99**	Rabi Safflower	730	950 (30)	109**
	Finger millet	1460	1870 (28)	116**	Pigeonpea	650	870 (34)	105**	Rabi Sunflower	580	780 (34)	203NS
	Rabi sorghum	1330	1690 (27)	168**	Chickpea	770	1020 (32)	81**				
	Wheat	1000	1380 (37)	158**								

Note: *FP* farmers' practice, *IP* improved practice, figures in parentheses indicate percentage over farmers' practice, **$P < 0.01$; *$P < 0.05$, *NS* not significant

Table 19.5 Gross and additional income for cereals, legumes, and oilseed crops under FP and IP in Bhoochetana, Karnataka

Crop year	Cereals				Legumes				Oilseeds			
	Major Crop	Income (Rs. ha^{-1})		Addl. income (Rs. ha^{-1})	Major crop	Income (Rs. ha^{-1})		Addl. income (Rs. ha^{-1})	Major Crop	Income (Rs. ha^{-1})		Addl. income (Rs. ha^{-1})
		FP	IP			FP	IP			FP	IP	
2009–2010	Maize	45,528	65,520	19,992	Chickpea	20,064	25,872	5808	Groundnut	22,680	31,290	8610
	Finger millet	15,372	23,333	7961					Kharif sunflower	17,942	24,808	6867
	Rabi sorghum	10,578	15,308	4730					Soybean	23,895	35,370	11,475
2010–2011	Kharif sorghum	15,390	20,700	5310	Blackgram	19,530	26,460	6930	Groundnut	34,500	48,990	14,490
	Maize	51,216	66,528	15,312	Greengram	14,899	20,922	6023	Kharif sunflower	13,865	16,920	3055
	Pearl millet	14,872	19,800	4928	Pigeonpea	36,000	48,600	12,600	Soybean	27,020	35,560	8540
	Finger millet	18,432	25,283	6852	Chickpea	28,980	38,010	9030				
	rabi sorghum	12,330	17,640	5310								
2011–2012	Kharif sorghum	20,800	29,100	8300	Blackgram	22,110	29,370	7260	Groundnut	31,320	43,470	12,150
	Maize	38,220	50,078	11,858	Cowpea	9450	14,000	4550	Kharif sunflower	30,240	40,880	10,640
	Paddy	46,872	55,296	8424	Fieldbean	29,800	38,800	9000	Soybean	24,420	32,835	8415
	Pearl millet	17,934	24,892	6958	Greengram	18,900	26,600	7700	Rabi safflower	13,140	17,280	4140
	Finger millet	15,750	20,580	4830	Pigeonpea	29,280	40,320	11,040	Rabi sunflower	35,500	49,250	13,750
	Rabi sorghum	14,500	19,100	4600	Chickpea	25,760	33,880	8120				

2012–2013	Kharif sorghum	31,160	40,584	9424	Blackgram	52,460	70,520	18,060	Groundnut	34,410	45,140	10,730
	Maize	43,475	56,988	13,513	Fieldbean	21,750	29,000	7250	Kharif sunflower	37,370	48,840	11,470
	Paddy	45,375	57,500	12,125	Greengram	36,960	48,840	11,880	Soybean	23,320	30,800	7480
	Pearl millet	15,275	21,033	5758	Horsegram	5500	7150	1650	Rabi safflower	14,280	18,200	3920
	Rabi maize	25,733	36,425	10,693	Pigeonpea	37,730	48,125	10,395	Rabi sunflower	26,640	35,150	8510
	Finger millet	20,700	27,450	6750	Chickpea	18,900	24,600	5700				
	Rabi Sorghum	18,392	24,168	5776								
	Wheat	8235	10,935	2700								
2013–2014	Kharif sorghum	32,072	42,104	10,032	Blackgram	24,510	32,680	8170	Groundnut	52,400	68,000	15600
	Maize	53,710	69,954	16,244	Cowpea	12,800	17,200	4400	Kharif sunflower	37,740	51,430	13,690
	Paddy	52,269	64,714	12,445	Fieldbean	19,200	26,400	7200	Soybean	37,000	46,500	9500
	Pearl millet	17,625	24,500	6875	Greengram	20,250	26,550	6300	Rabi safflower	21,900	28,500	6600
	Finger millet	21,900	28,050	6150	Pigeonpea	27,950	37,410	9460	Rabi sunflower	21,460	28,860	7400
	Rabi sorghum	20,216	25,688	5472	Chickpea	23,870	31,620	7750				
	Wheat	14,000	19,320	5320								

In percentage terms, the improved practices were very much effective as the improved practice helped to improve the profitability by 18–52% across cereal crops from 2009 to 2013. The highest yield profitability was observed in finger millet (52%) during 2009. It is significant to note that the soil test-based fertilizer application along with micro and secondary nutrients resulted in enhanced yield of finger millet. Similarly, rabi sorghum (45%) and maize (44%) also showed impressive yield benefits during the same period. Although the percentage increase in yield benefits was impressive, the absolute numbers showed a declining trend during dry and very dry years. In terms of legume crops, the highest percentage of yield increment was achieved in cowpea (45%) followed by green gram (42%) between farmers' practice and improved practice. There is a mixed yield response over farmers' practice in different rainfall years. Similarly, soybean (48%) and groundnut (42%) showed significant yield improvement over farmers' practice during 2009 and 2010, respectively (Table 19.5).

It was clearly demonstrated that rainfall variation had impact on crop yield, and as a result, the yield gain was reduced during low rainfall years. However, crop yield was considerably higher when compared with farmers' practice. It showed that the use of micronutrients, new cultivars, and other improved practices had greater effect on the crop yield. Legume crops and oilseed crops also performed well throughout the project period. Since legumes form major part of staple food crops in the state, efforts are needed to revive the legume-based cropping system with new knowledge, practices, methods, and approaches.

19.8.2 Economic Benefits and Livelihood Improvement

Table 19.5 compares the gross income and net additional income for different crops between Farmers' Practice (FP) and Improved Practice (IP) in different years. Among cereal crops, maize is more remunerative as the additional income was highest (ranging between Rs. 11,850 and 19,900 ha^{-1}) in all the years over other cereal crops followed by paddy (ranging between Rs. 8424 and 12,400 ha^{-1}), kharif sorghum (ranging from Rs. 5300 to 10,000 ha^{-1}), finger millet (ranging between Rs. 4830 and 7961 ha^{-1}), and rabi sorghum (ranging between Rs. 4600 and 5770 ha^{-1}). Similarly, blackgram, pigeonpea, and green gram are more remunerative among legume crops in different rainfall years. The highest additional income of Rs. 18,000 ha^{-1} was obtained from blackgram during 2012–2013 followed by pigeonpea (Rs. 12,600 ha^{-1}) and greengram (Rs. 11,800 ha^{-1}) during 2010–2011 and 2012–2013 season, respectively. Chickpea was grown in major areas and the additional income was ranging between Rs. 5700 ha^{-1} during 2012–2013 and Rs. 9000 ha^{-1} during 2010–2011 seasons, respectively. Among oilseed crops, groundnut recorded highest additional income (Rs. 15,600 ha^{-1} during 2013–2014) followed by sunflower (Rs. 13,600 ha^{-1} during 2013–2014) and soybean (Rs. 11,400 ha^{-1} during 2009–2010).

The impact of rainfall on crop yield and income was analyzed for major cereals, legumes, and oilseed crops in normal, dry, and very dry rainfall years (Table 19.6). To compare economic benefit from different crops, we have presented net additional

Table 19.6 Average crop yield, net income, and benefit-cost ratio of selected crops under improved practice and conventional farming practice with full cost in normal (2010), dry (2011), and very dry rainfall year (2012) in Karnataka

Crop	Mean rainfall (mm)	Yield (kg ha^{-1})			Net income (Rs. ha^{-1})	BC ratio
		IP	FP	Increase (%)		
2010–2011 (Normal rainfall year)						
Chickpea	759	1820	1350	34	9770	5.3
Greengram	800	760	550	40	7970	4.4
Pigeonpea	836	1630	1210	35	14,670	7.9
Groundnut	572	1810	1300	40	11,900	6.7
Soybean	863	2650	2010	32	9250	5.1
Pearl millet	685	2390	1710	40	6030	3.3
Maize	655	7250	5410	34	16,220	9.1
Finger millet	624	2320	1700	36	5960	3.5
Sorghum	614	2410	1780	36	5710	3.1
Mean	712	2560	1891	36	9720	5.4
2011–2012 (Dry year)						
Chickpea	407	1110	830	35	8030	4.4
Greengram	484	830	580	41	9620	5.4
Pigeonpea	473	1230	890	38	12,450	7.5
Maize	470	5270	3950	33	12,930	8.5
Paddy	2720	5580	4480	25	12,160	9.7
Pearl millet	415	2370	1710	38	6460	3.6
Finger millet	485	2040	1550	31	5100	3.8
Sorghum	451	3010	2150	40	8640	5.1
Groundnut	389	1900	1340	42	15,210	9.0
Soybean	520	1850	1320	41	9020	5.0
Mean	681	2519	1880	36	9962	6.2
2012–2013(Very dry year)						
Chickpea	382	780	600	30	5330	3.1
Greengram	592	1090	820	33	11,730	6.3
Pigeonpea	367	1040	810	29	9030	5.2
Maize	318	5080	3850	32	14,450	9.2
Paddy	1375	4770	3760	27	12,950	8.9
Pearl millet	380	1980	1490	33	5750	3.4
Finger millet	283	1680	1260	33	6300	4.4
Sorghum	388	2510	1940	29	8650	4.7
Groundnut	274	1030	780	33	9400	6
Soybean	465	1570	1170	34	8980	5.1
Mean	482	2153	1648	31	9257	5.6

income after subtracting the cost of cultivation from gross income both for farmers' practice and improved practice. Maize, pigeonpea, and groundnut are more remunerative during normal rainfall year (2010) as the yield of these crops were ranging from 7275 to 5435 kg ha^{-1}; 1631 to 1212 kg ha^{-1}; and 1814 to 1297 kg ha^{-1} under improved and farmers' practice, respectively. The increased yield was resulted in enhanced net additional income of Rs. 14,466, 10,634, and 10,157 ha^{-1} from maize, pigeonpea, and groundnut, respectively. On the other hand, other rainfed crops such as chickpea, soybean, and blackgram also performed better as the median yield increment was around 35% resulting in increasing net income of Rs. 6596, 7335, and 7784 ha^{-1} under moderate to good rainfall conditions.

The economic benefit due to improved technologies was evident even during low rainfall years. During dry year (year 2011), the crop yield of maize, pigeonpea, groundnut, and paddy increased significantly over farmers' practice but observed declining trend compared to 2010 (normal year) yield level. The net additional income obtained from improved practice was Rs. 11,836, 9561, 14,160, and 10,595 ha^{-1} for maize, pigeonpea, groundnut, and paddy, respectively. The same trend can be observed during 2012 (very dry year) also where the net income reduced compared to 2011 in the case of groundnut (Rs. 8160 ha^{-1}) and pigeonpea (Rs. 7748 ha^{-1}) but marginally increased for maize (Rs. 13,508 ha^{-1}) and paddy (Rs. 11,043 ha^{-1}). The effect of declining rainfall was more evident in all the years, except greengram and soybean, the yield of all other crops was reduced by almost 21–133% under improved practice when compared between normal (2009) and very dry year (2012). However, improved management practice helped to withstand the shock and subsequently increased net income.

19.8.3 Return on Investment

Table 19.4 compares the return on investment between IP and FP for different rainfall years from 2010–2011 to 2012–2013 and revealed that IP performed better in terms of return on investment (B:C ratio) during all the years. The mean additional B:C ratio for the year normal (2010–2011), dry (2011–2012), and very dry year (2012–2013) for major crops was 5.4, 6.2, and 5.6, respectively. Interestingly, IP has contributed to enhance the B:C ratio above the mean level for maize (9.1), pigeonpea (7.9), and groundnut (6.7) during normal rainfall year (2010–2011), while the same crops performed low during very dry year (2012–2013) due to poor rainfall. The BC ratio ranges from 3 to 10 depending on crop type, soil type, and rainfall condition. The comparison of IP with FP revealed that the improved management system as such performed better in terms of achieving higher return on investment by above 2.3:1 compared to 1.9:1 by FP even with full cost of cultivation including micronutrients over three different rainfall years. At the state level, the improved crop yield contributed to enhanced net income and additional value of the product. By the end of fourth year, the net profit accrued from the program is about Rs. 1248 crores (242 million US$) from 30 districts.

19.8.4 Social Impact of Bhoochetana

Bhoochetana program witnessed significant changes in terms of social as well as economic condition of farming households in Karnataka. To substantiate this view, we carried out a rapid survey of beneficiary households in selected districts. The results are most revealing.

19.8.4.1 Asset Formation

Most of the farm households who have adopted Bhoochetana technologies have reinvested additional crop income on asset formation particularly on agriculture and agriculture-related infrastructure (40% of households). The major proportions (13%) of households have also invested on white goods (luxury goods) such as fridge, ceiling fan, mixer grinder, mobile, and vehicles. It is important to note that about 10% of the households have invested income obtained from Bhoochetana on loan repayment, house infrastructure, and education, respectively. The additional income was useful for majority of households (7%) to overcome health-related expenditure which is significant as it ensures better working condition for the family members. The Bhoochetana program also helped to take care of domestic expenditures as it facilitates small savings due to crop improvement (Fig. 19.5).

19.8.4.2 Knowledge Improvement

Bhoochetana is a holistic process-based mission project which intended to not only increase crop productivity but also enhance stakeholders' knowledge regarding agriculture operations. The analysis covered major activities which are part of Bhoochetana mission project, and periodic trainings/capacity building programs

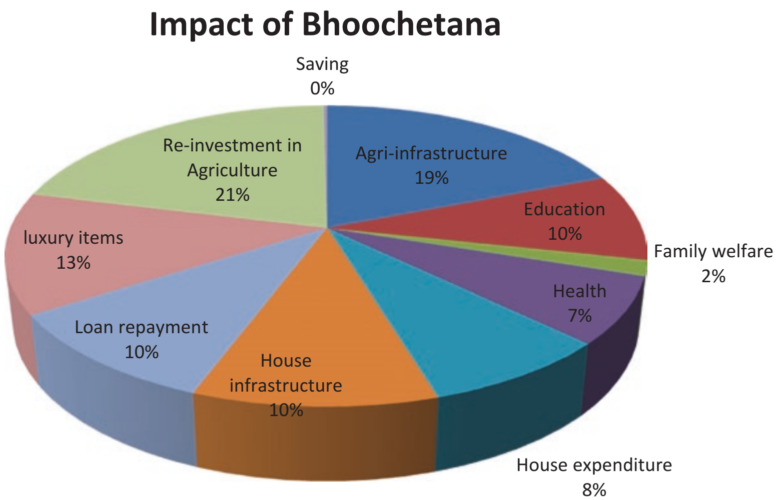

Fig. 19.5 Contribution of Bhoochetana for household asset formation, reinvestment on agriculture, health, and education due to increased income in Karnataka

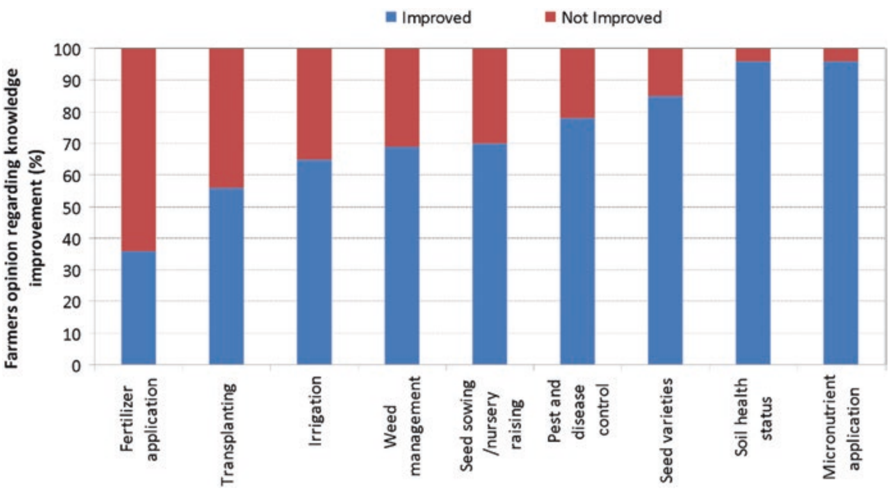

Fig. 19.6 Bhoochetana contributed to increased farmers' knowledge regarding agriculture development in Karnataka

were organized to disseminate the knowledge. The results are more revealing. First, the knowledge dissemination process initiated by ICRISAT through master trainers from University of Agricultural Sciences and Department of Agriculture impacted most positively on farmers as more than 50% of the households have acknowledged improved knowledge on major aspects of agriculture development in the state. Second, the knowledge about soil health status, micronutrient application, and seed varieties improved significantly which are critical components of agriculture development. More than 85% of rural households reported that their knowledge enhanced on these critical components. Third, nearly 80% of households have learnt new methods to control pests and diseases to enhance their crop yield in the rainfed agriculture (Fig. 19.6).

19.8.4.3 Gender Equity

Gender equity issue was addressed by analyzing the decision-making process by men and women farmers who are following Bhoochetana practices. The analysis revealed that women exclusively have very meager role in decision making with regard to selection of crop, variety, land preparation, fertilizer and manure application, irrigation, harvesting, threshing, and marketing (Fig. 19.7). However, most of the critical decisions related to above-mentioned activities were taken jointly which shows that there is a consensus among men and women to carry out agriculture activities in the dryland areas. It is evident that women are mostly involved in laborious activities on which they have decision-making control, viz., transplanting (23%), hand weeding (19%), and interculture (12%). It is worth mentioning that men have greater control over decision making in marketing which is the critical aspect of financial management. More than 70% of the men and women farmers

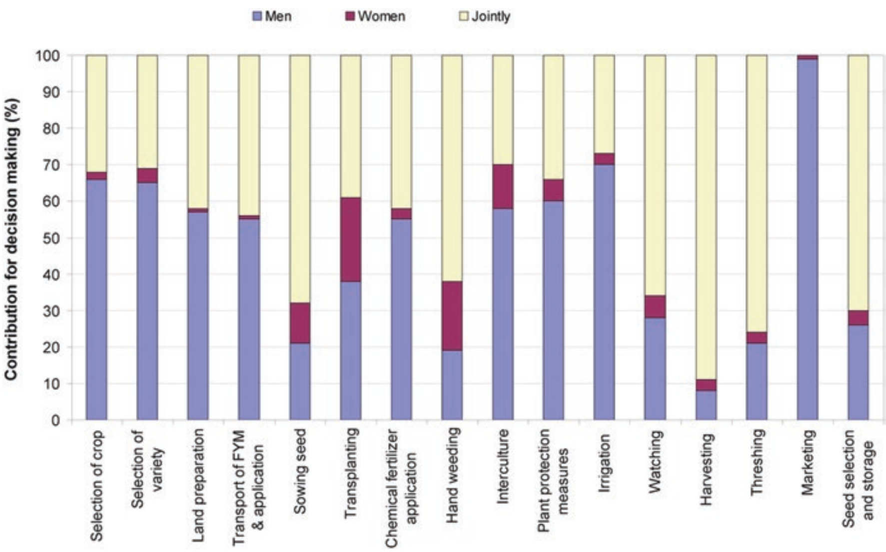

Fig. 19.7 Bhoochetana implementation helped to minimize gender inequality and enhanced decision making of women and men in agriculture-related activities

jointly made decision regarding harvesting, threshing, seed selection, and storage. This reflects that certain activities essentially benefited with women's decisions which are critical in agricultural operations.

19.8.5 Taking Soil Management at Farmers Doorsteps: The Innovations

Bhoochetana initiative originated with the proposition to explore new ways of thinking about interventions that could promote agricultural development by better enabling the partnership process. *Bhoochetana* provided a platform for better resource allocation with added responsibility among partners. The convergence of programs/schemes and knowledge was useful in allocating human as well as financial resources in this program. In *Bhoochetana*, all major programs in the Department of Agriculture converged and treated as "single file system." The major chunk of resource is from central government (75%) and the remaining share is from the state government (25%). One lesson emerged out of which is that research and development practitioners, line departments, and non-state actors must be willing to work with emerging concepts and must recognize that the interventions that they are planning will evolve while they learn. The partnership concept provides a framework for inclusive, knowledge-intensive agricultural development, but more focused, committed efforts are required to accomplish the goal of disseminating pro-poor technologies for small and marginal farmers for better impact.

The Bhoochetana partnership has explored new ways of extension system which is unique in its composition and functioning. It is essential that the traditional extension system may be exchanged for this model where research supports innovation at the local level. The important lesson was that research systems need to be supported in developing interface with other sectors to prioritize and address research issues to achieve desired growth in agriculture sector. Major attention must be given to how and why the research system is governed and to the ability and the attitudes required for engaging in partnerships. Attention must also be given to putting public awareness strategies in place through print and mass media along with training and exposure activities. These types of changes are not necessarily expensive, but they are preconditions for effective investment in research that can contribute to innovation. Similarly, extension investments should create the capacity to identify new, promising alternatives at the farm level and ensure that they are supported in the right way through engaging potential partners.

The soil health mapping was one of the entry point interventions in this initiative and based on the soil health mapping of the whole state in 2009–2010, taluk-wise balanced and integrated nutrient management recommendations were developed as against to state-level recommendations and disseminated to the farmers through farmer facilitators, wall writings, soil health cards, and internet. In addition, it also ensured the availability of these inputs at the village level through appropriate institutional mechanism.

Soil health cards were provided in local language (Kannada) to individual farmers whose fields were sampled with details of individual nutrient status and critical limits along with a comment on the nutrient status of the field. The card was printed both sides containing basic information about the farmer field and recommended dose of nutrients for each crop as well as quantity of nutrients available in commercially marketed fertilizers, for the understanding of farmers. For maximum reach of information to farmers/stakeholders, a multi-pronged information dissemination systems was adopted. Wall writing is one such mechanism through which appropriate information was disseminated in each and every village to create awareness among the farmers. Wall writings were quite conspicuous with details of soil health status, input quantities supplied to the farmer per hectare, component of subsidy, crop cultivars, etc. Wall writings were the effective communication channels in rural areas which has gained movement in Bhoochetana on a large scale helping farmers to understand their soil and agricultural practices, objective of the program, and areas to be covered by the program. Additionally, thousands of brochures and handouts were published and distributed in each district on improved management practices, information on nutrients status, nutrients recommended taluk-wise, and widely distributed in all districts. In addition, print media news coverage was extensive to introduce Bhoochetana program to farmers and also on activities during the season in all districts, besides field facilitators and lead farmers contacts with individual farmers in selected village.

An innovative extension system coupled with institutional intermediaries and high level monitoring helped to reach more than 4 million farming families in the state covering almost 5 million ha area. The cumulative effect of integrated management approach helped to achieve higher benefit-cost ratio for major crops in the state. The soil test-based nutrient management along with other improved technologies increased crop yields up to 66% as compared to farmers' practice (Wani et al. 2012a). The adoption of improved management practices such as soil test-based nutrient application, improved crop cultivars, pest management and suitable land, and water management practices helped to sustain the crops and tolerant to increasing droughts situation and pests and diseases resulting in increased yield compared to conventional farmers' practice. This is evidenced not only during normal years but also during dry and very dry years, thereby indicating improved management practices are critical in building the resilience of the farming system with increased climate variability.

In case of Bhoochetana, science-led innovative approaches were implemented to realize higher yield with modifications in soil, water, and crop management technologies. These kinds of modifications in crop management often require significant changes in technological and economic support to the farmers especially in regions where farmers are not accustomed to using micronutrients to rejuvenate the soil and enhance the yield. Thus, rainfed areas of semiarid regions could be more favorable for adoption of this integrated approach because farmers are more receptive towards new interventions and familiar with integrated technologies to enhance the crop yield.

The Bhoochetana program demonstrated the technical performance of science-led interventions at field level through action research. There is a need to understand major drivers and hindrances beyond field level. An understanding of market conditions, interactions among stakeholders, and other institutional and political dimensions become important to achieve large number of farmers and ensuring profitability for the farmers. The availability of inputs such as seeds, fertilizers, micronutrients, and crop protection chemicals ensures agricultural operations easy, and timely sowing and planting is possible. The same applies to farmers' access to credit and to markets for agricultural inputs and produce. The innovative institutional arrangements helped to reach out millions of farmers with improved knowledge at their door step.

19.9 Organic and Biological Fertilizers for Sustainable Soil Health

Role of soil organic C in maintaining soil health is well documented (Wani et al. 2012b) and low soil organic C in tropical soils is a major factor for poor crop productivity (Lee and Wani 1989; Edmeades 2003; Ghosh et al. 2009; Materechera 2010). Therefore, improving soil organic C levels through additions of organic manures to improve soil physical, chemical, and biological functions is need of the day for sustainability. The large quantities of about 700 million ton of organic wastes are generated in India (Bhiday 1994) which offers opportunities to convert those into valuable composts rich in organic C and macro, micronutrients.

The vermicomposting is an effective technology to produce quality compost using *Eudrilus Eugeniae* and *Eisenia fetida* species of earthworms. Rock phosphate (a cheap source of P) may be added at 3–4% of composting biomass to improve P content in vermicompost due to solubilization action of humic acids and phosphate solubilizing bacteria (Hameeda et al. 2006) during vermicomposting process. Similarly, a microbial consortia culture of 21 bacterial isolates belonging to genus Bacillus (8 isolates), Halobacillus (3), Staphylococcus (3), Microbacterium (1), Streptomyces (1), and one actinomycetes isolated from microbial culture (Excel Crop Care Ltd) is equally effective in rapidly converting wastes into useful compost, wherein the bacterial population in consortium culture found is 4.5×10^{-7} cfu ml^{-1} at 10^{-6}.

In field studies, the integrated nutrient management (INM) involving the use of enriched compost has been found effective to cut cost of chemical fertilizers up to 50% while recording at par yields or more than balanced nutrition solely through chemical fertilizers (Chander et al. 2013a). As the composts are prepared from on-farm wastes, the benefit-cost ratios are significantly improved. Similarly, plant part nutrient contents also tended to improve under INM. Further, applied compost along with secondary and micronutrients found to show residual benefits as increased crop yields for succeeding three seasons. So, results showed that INM is economically beneficial for producing more food, while leading to resilience building of SAT production systems.

The microbial activities in soil-plant systems are responsible for nutrient transformation and so are major component of good soil health. Their external addition can enhance their activities for increasing fertilizer use efficiency. The non-symbiotic group of bacteria (*Azotobacter*/*Azospirillum)* in nonleguminous, while symbiotic (*Rhizobium)* in leguminous plants may be used to fix the atmospheric nitrogen and make it available to plants. Phosphorus solubilizing microorganisms (PSMs) can solubilize the complex insoluble form of phosphorus into simple soluble forms that can be taken up by plants. Similarly, vesicular arbuscular mycorrhizae (VAM) infects roots, increases effective root surface, and soil volume explored for nutrient uptake through extensive mycelia along with solubilizing effect by chemicals released.

19.10 Landform Management for Cultivating Rainy Fallows in Vertisols

Vertisols and associated soils which occupy large areas globally (approximately 257 million ha, Dudal 1965) are traditionally cultivated during the post-rainy season on stored soil moisture. Due to poor infiltration rates and water logging, farmers are facing difficulties to cultivate during the rainy season. It is perceived that the practice of fallowing Vertisols and associated soils in Madhya Pradesh, India have decreased after the introduction of soybean. However, 2.02 M ha of cultivable land is still kept fallow in Central India, during the kharif season (Dwivedi et al. 2003). On-farm soybean trials conducted by ICRISAT involving improved land configuration (BBF) and short-duration soybean varieties along with growing chickpea with minimum tillage in *rabi* season enhanced the cropping intensity in Guna, Vidisha, and Indore districts of Madhya Pradesh. Increased crop yields (40–200%) and incomes (up to 100%) were realized with landform treatment, new varieties, and other best-bet management options (Wani et al. 2008, 2016) through crop intensification.

19.11 Soil Management for Intensifying Rice Fallows

Rice fallows are big opportunities to improve productivity and livelihoods through proper soil fertility management to support two good crops. Considerable amount of green water is available after the monsoon, especially in the rice-fallow systems, which could be easily utilized by introducing a short duration legume crop with simple seed priming and micronutrient amendments (Kumar Rao et al. 2008; Wani et al. 2009a, b; Singh et al. 2010). About 14.29 million ha (30% of rice growing area) rice fallows are available in Indo Gangetic Plains (IGP) spread in Bangladesh, Nepal, Pakistan, and India, out of which 11.4 M ha (82%) are in Indian states of Bihar, Madhya Pradesh, Chhattisgarh, Jharkhand, West Bengal, Odisha, and Assam (Subbarao et al. 2001). Taking advantage of the sufficiently available soil moisture after harvesting the rice crop, during the winter season in the eastern India, growing of early maturing chickpea in rice-fallow areas with best-bet management practices provides opportunity for intensification (Kumar Rao et al. 2008; Harris et al. 1999). An economic analysis has shown that growing legumes in rice fallows is profitable for the farmers with a B:C ratio exceeding 3.0 for many legumes. In addition, utilizing rice fallows for growing legumes could result in the generation of 584 million person-days employment for South Asia and make the country self-sufficient in pulses production.

19.12 Soil Management and Ecosystem Services

19.12.1 Nitrogen Use Efficiency

Soil management for correcting deficiencies of emerging secondary and micronutrients like S, B, and Zn is found not only improving productivity and incomes directly, but also nitrogen use efficiency (NUE) (Chander et al. 2014a; Wani et al. 2015b). Nitrogen (N) is often the most limiting nutrient for crop yield in many regions of the world (Giller et al. 2004) and in a quest to achieve high yields, it is applied in large quantity from external sources, resulting in low nitrogen use efficiency (NUE) which is approximately 33% for cereal production (Raun and Johnson 1999). Inefficient use of N fertilizer is causing serious environmental problems associated with the emission of NH_3, N_2, and N_2O to the atmosphere and contamination of ground and surface water resources via nitrate leaching or runoff (Singh and Verma 2007). In response to continually increasing economic and environmental pressures, there is an urgent need

Table 19.7 Effects of balanced nutrient management strategies on nitrogen efficiency indices in maize at ICRISAT, Patancheru, India, rainy season 2010

Treatment	NUpE	NUtE	NUE	NHI
Control	1.00	60.2	60.2	46.8
NP	0.37*	80.7*	30.1*	67.3*
NP+SBZn (every yr)	0.46*	78.5*	36.0*	60.5*
NP+50%SBZn (every yr)	0.51*	92.5*	47.3*	65.8*
NP+SBZn (alternate yr)	0.47*	84.4*	39.7*	69.3*
NP+50%SBZn (alternate yr)	0.42*	80.8*	34.1*	67.0*
LSD (5%)	0.11	17.4	8.85	11.3

NUpE (Nitrogen uptake efficiency) = Total plant N uptake/N supply [*N supply means sum of N applied as fertilizer and total N uptake in control*]; *NUtE* (N utilization efficiency) = Grain yield/Total plant N uptake; *NUE* (N use efficiency) = Grain yield/N supply; NHI (N harvest index) = N in grain/Total N uptake
*significant at $p \leq 0.05$
Source: Chander et al. (2014a)

to enhance efficient use of nitrogenous fertilizers and increase profitability by developing sustainable farming systems (Mahler et al. 1994). The results (Table 19.7) have shown that the addition of deficient S, B, and Zn records the highest uptake efficiency, utilization efficiency, use efficiency, and harvest index in cereal production and 50% dose of S, B, and Zn is better than 100% S, B, and Zn addition once in 2 years (Chander et al. 2014a; Wani et al. 2015b). Nutrient uptake efficiency (NUpE/PUpE) reflects the efficiency of the crop in obtaining it from the soil (Rahimizadeh et al. 2010). Uptake of supplied nutrient is the 1st crucial step and an issue of concern worldwide, and hence increased nutrient uptake efficiency has been proposed as a strategy to increase nutrient use efficiency by Raun and Johnson (1999). Nutrient utilization efficiency (NUtE/PUtE) reflects the ability of the plant to transport the nutrient uptakes into grain (Delogu et al. 1998). Nutrient harvest index (NHI/PHI), defined as nutrient in grain to total nutrient uptake, is an important consideration in cereals. NHI/PHI reflects the grain nutritional quality (Hirel et al. 2007).

19.12.2 Rainwater Use Efficiency

Water is a scarce resource and chief determinant of poverty and hunger in rural areas, so improving rainwater use efficiency (RWUE) is important for achieving food security and better livelihoods. Soil test-based balanced fertilizer use is found to produce more food with less water and significantly increased rainwater use efficiency in crops by channelizing unproductive evaporation loss into productive transpiration (Chander et al. 2014a). In studies in Rajasthan (Table 19.8), the RWUE of existing farmers' cultivars with applied N and P in maize varied between 3.36 and 7.39 mg kg^{-1} ha^{-1}(Chander et al. 2013b). The introduction of improved cultivar in on-farm trials in target districts increased it from 5.43 to 10.8 mg kg^{-1} ha^{-1} and

Table 19.8 Integrated improved crop cultivar and balanced nutrient management enhance maize grain yield and rainwater use efficiency in Rajasthan during rainy/kharif season 2009

District	Yield (kg ha^{-1})			LSD (5%)	B:C ratio	Rainwater use efficiency (kg mm^{-1} ha^{-1})			LSD (5%)
	FP	IC	IC+BN			FP	IC	IC+BN	
Tonk	1150	1930	3160	280	4.26	3.36	5.52	9.13	0.73
Sawai Madhopur	1430	2030	3000	420	3.33	4.09	5.77	8.59	0.95
Bundi	1380	2180	4240	714	6.05	3.59	5.68	10.93	1.68
Bhilwara	2990	4340	6510	860	7.45	7.39	10.76	16.15	1.69
Jhalawar	2550	3520	4960	316	5.11	4.21	5.82	8.20	0.52
Udaipur	2530	3090	6320	509	8.03	4.45	5.43	11.11	0.89

Note: *FP* farmers' practice, *IC* improved cultivar, *BN* soil test-based balanced nutrition, *B:C* benefit to cost ratio
Source: Chander et al. (2013b)

thereby proved the ability of improved cultivars to best utilize the limiting water resources. The integrated approach involving soil test-based addition of fertilizers including micronutrients to improved cultivar, however, recorded the maximum RWUE (8.20–16.2 mg kg^{-1} ha^{-1}) (Chander et al. 2013b). Therefore, integrated soil and crop management involving improved crop cultivars and soil fertility management, with a purpose to increase proportion of water balance as productive transpiration, is one of the most important rainwater-management strategies to improve yields and water productivity (Rockström et al. 2010).

19.12.3 Soil Organic C and Health

Results at long-term experiment at ICRISAT headquarter showed that improved system comprising of landform management (broadbed and furrow cultivation), soil test-based balanced fertilization, and crop management not only increased crop productivity, but also increased soil organic C content (Table 19.9). An additional quantity of 7.3 t C ha^{-1} (335 kg C ha^{-1} $year^{-1}$) was sequestered in soil under the improved system compared with the traditional system over the 24-year period (Wani et al. 2003a). It was concluded that C inputs increased with continuous cropping, particularly where soil test-based fertilizers were applied and when legumes were included in the system. Soil microbial biomass C responds more rapidly than soil organic C to changes in management, and serves as a surrogate for soil quality. Improved management of Vertisols also resulted in higher (10.3 vs. 6.4%) biomass C as a proportion of soil organic C up to 120 cm soil depth. Along with improvements in soil organic C, the contents of available nutrients are also found to be improved under soil test-based managed plots (Chander et al. 2014b). The addition of needed nutrients and a positive relationship of soil organic C with available nutrients explain improvement in soil health (Wani et al. 2003a; Chander et al. 2014b).

Table 19.9 Effect of balanced nutrient and best practices on soil C and other properties

Property	System	Soil depth (cm)	
		0–60	60–120
Organic C (t C ha^{-1})	Improved	27.4	19.4
	Traditional	21.4	18.1
Microbial biomass C (kg C ha^{-1})	Improved	2676	2137
	Traditional	1462	1088
Microbial biomass N (kg N ha^{-1})	Improved	86.4	39.2
	Traditional	42.1	25.8
Total N (kg N ha^{-1})	Improved	2684	1928
	Traditional	2276	1884
Olsen-P (kg P ha^{-1})	Improved	6.1	1.6
	Traditional	1.5	1

Source: Wani et al. (2003a)

19.12.4 Resilience Building

Soil need based management is found to improve soil health through balancing deficiencies of secondary and micronutrients and low levels of soil organic C (Fig. 19.8). In pilot studies in Madhya Pradesh and elsewhere (Wani et al. 2016), the applied secondary and micronutrients (the alternate years) showed residual benefits in crop yields between 5 and 27% up to three succeeding seasons. In economic terms, added micro and secondary nutrients produced more food worth 1840 to 6900 ha^{-1} during each of the succeeding three seasons. The results clearly showed that balanced nutrition is not only economically remunerative in the season-1 of application but also leads to resilience building of production systems.

19.13 Experiences and Learnings

19.13.1 Soil Health Mapping: A National Strategy

Soil sampling is most important, but the weakest link in soil health assessment process as the smallest of amount of sample collected should represent millions of kilogram of soil in the field. Considering the huge financial and human resources required, samples cannot be collected in very large numbers, while there should not be compromise with the quality of results. There should be a balance between what is desirable and what is achievable through the following stratified sampling technique (Sahrawat et al. 2008). Soil samples need to be collected in grids representing effectively the topography, soil texture, soil color, farm sizes, cropping systems, and management practices. The involvement of farmers in collecting soil samples is important; though it is time consuming, but this will generate ownership and make it easier to scale up the soil test-based recommendations.

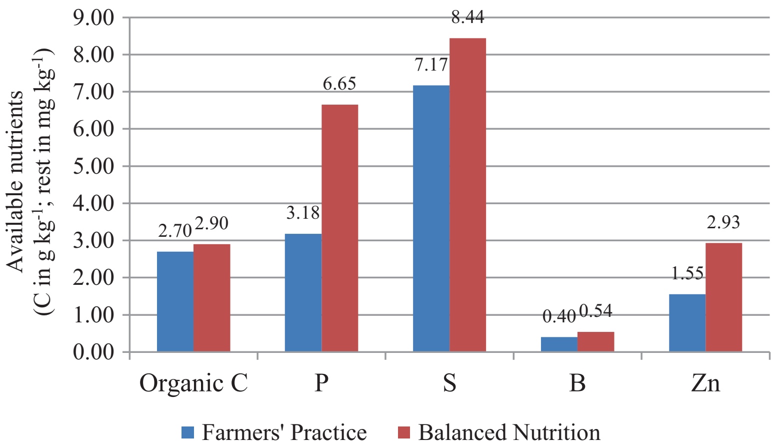

Fig. 19.8 Effect of farmers' practice and balanced nutrition on postharvest soil fertility status under rainy/kharif season groundnut in Nalgonda district (Andhra Pradesh) during 2010

The ensured quality, protocols, and processes for accreditation of laboratories are most important. The quality assurance standards as well as mechanisms to ensure quality analysis by the accredited labs by empowering leading institutions are another important aspect to be taken care of.

Soil test-based fertilizer recommendations including deficient micro and secondary nutrients should be developed at block (cluster of villages) level. ICRISAT's experience in pilot studies demonstrates the benefits of this approach. Subsequently, we can move towards village and farmer-based recommendations as awareness develop among the farmers, and the government is geared up to handle knowledge dissemination for villagers and individuals.

Over the years, farmers have increased their reliance on chemical fertilizers and have abandoned or reduced the use of organic manure drastically. Long-term experiments have clearly demonstrated increased sustainability of systems with Integrated Nutrient Management (INM) strategies including harnessing the biological sources and using legumes in crop rotation, organic manure, and soil test-based inorganic fertilizers for different crops. Incentives are required to promote the use of organic manure/fertilizers as well as biological sources like bio-fertilizer in order to encourage farmers to adopt integrated nutrient management approach. These recommendations need to be tethered to the soil test results. This presents a major challenge as the nutrient content of organic manures and fertilizers is highly variable. There is an urgent need to look at policies and innovative institutional arrangements for ensuring quality supply of bio-fertilizers and organic manure to the farmers by recycling organic wastes generated both in urban and rural areas. Mechanisms should be developed for recycling the organic wastes through aerobic-compost, vermicomposting, or other methods so that the farmers can use the recycled organic matter for crop production.

Moreover, micro-irrigation systems can be effectively used for the regulated supply of essential plant nutrients through fertigation and addition of micronutrients and secondary nutrients based on soil tests.

19.13.2 Micro Watershed as Implementation Unit

Managing soil and water efficiently under different agro-ecosystems is a challenging task and it can be done in the best possible way in a micro catchment, i.e., watershed scale. These watersheds can be integrated into meso- and macro-watersheds and further into subbasins and basin level for the effective planning, management, monitoring, and achieving the impact.

19.13.3 Land Use Planning Based on Land and Agro-Ecological Capability

However, such land use planning could be promoted through incentivizing the farmers to adopt the recommended cropping system. Penalties shall also be applied in terms of not providing the incentives and market support for crops that are not to be grown in a given agro-ecoregion.

19.13.4 Seeing is Believing: Sites of Learning and Innovations

Undertaking the innovations and piloting new developments in each district would require pilot sites to be established as exemplar sites for training as well as developmental purposes. Such sites of learning need to be developed by the scientific institutions by adopting the consortium approach and building public–private partnership. These sites of learning would also provide field laboratories for undertaking strategic research in the area of soil management strategies as well as impact assessment, monitoring, and evaluation studies.

19.13.5 Skill Development

For holistic development, new skills such as soil health mapping and precise fertility management, simulation modeling, use of remote sensing, online monitoring, and ICT-based knowledge dissemination need to be developed. This can be accomplished by retooling the present actors and bringing in the new actors having expertise in the new science areas. The stakeholders should be aware about the importance of various activities and their benefits in terms of economic, social, and environmental factors. Therefore, organizing various training at different scales is important.

19.13.6 Rejuvenating Extension System

Main reason for the existing large yield gaps between what farmers' harvest and the researchers pilot site yield is largely due to the knowledge gap between What to Do and How to Do it? In spite of a number of new/improved technologies, the farmers continue to do their farming business in a traditional manner. The reasons are multifarious as the current knowledge delivery system to the farmers, i.e., extension system is very inefficient and does not benefit the farmers. Therefore, there is an urgent need to reform the knowledge delivery systems by using innovative partnerships, tools, approaches, and methods. Past experiences suggest that the information delivery mechanism can be strengthened by utilizing the services of practicing farmers in the villages through Farmers' Field Schools and Farmer Facilitators who stay in the villages for most of their time, unlike the outside experts who visit villages once in a while (Wani et al. 2012a). The mix of tools like soil health cards, wall writings, awareness campaigns, traditional folk media, learning sites, ICT tools like mobile and internet-based soil health maps, farmer-to-farmer videos, pico projectors, and other tools has proved very effective in disseminating soil health and other management options in the watersheds.

19.13.7 Use of High-Science Tools and ICT for Planning, Implementation, and Monitoring

Science tools like remote sensing images and data, soil health mapping, scenario development simulations along with Geographical Information System (GIS), and soft skill planning participatory tools need to be used. GIS techniques help in estimating the important variables such as soil nutrient status based on interpolation technique. In addition, system modeling is also one of the emerging techniques which guides about resource availability, its management, and various alternatives to achieve yield potential. As trained human resource is major constraint in agriculture extension system, various information communication tools (ICT) are available which can bridge the gap between farmer and knowledge generator.

19.13.8 Building Partnerships Through Consortium and Convergence Approach

A watershed is a complex system with a multitude of problems. It requires a holistic approach that considers social, economic, political, and institutional factors to achieve specific social objectives (Dixon and Easter 1986; Wani et al. 2003b). The past experience showed that enhancing partnerships and institutional innovations through the consortium approach was the major impetus for harnessing the potential of community watershed management to reduce poverty and environmental degradation (Shambu Prasad et al. 2006). The underlying element of the consortium approach is to engage a range of actors to harness their strengths and synergies with the local community as the primary implementing unit. Through the consortium approach, complex issues can effectively be addressed by the joint efforts of key partners, namely the National Agricultural Research System (NARSs), nongovernmental organizations (NGOs), government organizations, international institutions, agricultural universities, community-based organizations, and other private interest groups, with farm households as the key decision makers. Thus, consortium approach brings together the expertise of different areas to expand the effectiveness of the various watershed initiatives and interventions.

19.13.9 Public–Private Partnership

The Public–Private Partnerships (PPPs) are viewed as the governance strategy to minimize the transaction costs and coordinating and enforcing relations between the partners engaged in the production of goods and services. They enable an optimal policy approach to promote the social and economic development, thus bringing together efficiency, flexibility, and competence of the private sector along with the accountability, long-term perspective, and social interest of the public sector. For soil health management, there is a need to identify business models for devolving the responsibilities of sample collection and soil analysis while ensuring quality standards as well as economic feasibility and also explore public–private partnerships involving fertilizer manufacturers, private service providers, state agricultural universities, and selected Krishi Vigyan Kendras.

19.14 Conclusions

Soil management for correcting fertility levels proved an effective technology to improve productivity levels and livelihoods, and this is a low hanging big opportunity in drylands for benefitting the farmers. Lack of awareness and required infrastructure are big hurdles to take these benefits to large number of farmers. Majority of farmers in the drylands are the smallholders and therefore would need policy support to implement soil fertility management for improving system productivity and livelihoods. Increasing soil fertility levels can also facilitate taking 2nd chickpea crop in rice fallows. Soil landform management in Vertisols is an effective technology to cultivate rainy fallow without compromising with 2nd post-rainy season crop; however, required capacity building of farmers and stakeholders is most important for effectively implementing it. Efficient soil management needs to be promoted not only for improving productivity and livelihoods, but also for beneficial effects on ecosystem services like enhanced fertilizer and water use efficiency and C-sequestration.

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The Relevance of Traditional Ecological Knowledge (TEK) in Agricultural Sustainability of the Semi-Arid Tropics

20

Seema B. Sharma

Abstract

Boosting the agricultural production to feed the increasing world population and at the same time managing the ecosystem sustainability is the greatest challenge that the scientists, farming community and the policy makers face in the present scenario. Strategies to maintain and improve agricultural production via input of synthetic chemicals have already raised questions in their long term environmental implications. In the past two decades agricultural activities have witnessed higher inputs of chemicals due to government policies to promote chemical fertilisers and farmer's greed to have higher yields in short term. Consequently, the resource scarce farmers are giving up their indigenous knowledge of natural farming practices which can sustain them and the agro-ecosystems in the long run. Agro-ecosystem management strategies based on traditional ecological knowledge (TEK) are gaining importance due to their better adaptability and sustainability. TEK is the knowledge database and adapted practices of indigenous and local communities around the world. World over, especially in India, there is enormous wealth of TEK but it is being lost and is surviving only in bits and pieces. The present chapter deals with the relevance of these TEK based systems in dealing with the issues of better soil management and achieving overall goal for agricultural sustainability.

Keywords

Traditional ecological knowledge • Agriculture • Soil • Sustainability • Nutrient management • Semi-arid tropics

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20.1 Introduction: What is TEK?

Traditional knowledge is the knowledge database, and adaptive practices of indigenous and local communities around the world. It is developed from experience gained over a long period of time and adapted to the local culture and microenvironment. It is collectively owned and takes the form of stories, songs, proverbs, folklore, cultural values, beliefs, rituals, community laws and agricultural practices, including the development of plant species and animal breeds (CBD 2016). Traditional knowledge originates from the actual needs, problems, interests and aspirations at home and in the communities; it takes birth in the fields, homesteads and forests. This is in direct contrast with the modern scientific method that originates in laboratories and after trials and errors reaches the end users. In the traditional creation of knowledge in agriculture, ideas, experiences and experimentation were widely shared and discussed. TEK is also known as 'indigenous knowledge', 'people's knowledge', 'traditional science' or 'traditional wisdom'. This knowledge is inherited by generations, generally by word of mouth and cultural practices, and has been the basis for agriculture, food preparation, education, health care, conservation and the wide range of other activities that sustain societies in many parts of the world. Traditional ecological knowledge has been defined as 'a cumulative body of knowledge, practice and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment' (Berkes 1999).

Some studies have suggested that TEK, having co-evolved with ecosystems (Long et al. 2003), holds strong chances of providing a strong foundation for ecological restoration (Turner et al. 2000; Long et al. 2003; Higgs 2005; Shebitz 2005). However, some scholars are sceptical about the scientific validation of traditional knowledge and its implication beyond the local level, while others are concerned about the ethics of exploiting traditional knowledge for academic and policy purposes (Chalmers and Fabricius 2007). Hence, incorporating traditional knowledge systems into ecological restorative measures is still a great challenge (He et al. 2009).

With some differences amongst them, terms such as traditional knowledge, traditional environmental knowledge, traditional ecological knowledge, indigenous knowledge, local ecological knowledge, and traditional ecological knowledge and wisdom are often used interchangeably depending on the context and use (Stevenson 1996; Berkes et al. 2000; Turner et al. 2000; Stevenson 2005; Charnley et al. 2007; Berkes 2008; Davis and Ruddle 2010; Rist et al. 2010).

20.2 Relevance of TEK in Agricultural Sustainability in Present Scenario of Climate Change

World over, especially in India, there is enormous wealth of TEK but it is on the verge of being lost and is surviving only in isolated domains. Injudicious use of chemical fertilisers and pesticides in farming systems has threatened the ecosystem in many ways. Subsidised prices of chemical fertilisers and governmental policies to promote the chemical intensive agricultural practices in conjugation with greed driven farming practices have crippled the soil system over the past four decades (Sharma et al. 2013). Consequently, the resource scarce farmers are giving up their indigenous knowledge of natural farming practices based on organic inputs, which can sustain them and the agro-ecosystems in the long run.

Although scientific intervention and Governmental aid have a considerable effect on the agri-management practices in fragile ecosystems, still TEK based adaptive management practices are location and region specific and have far more chances of adaptability as compared to generalised policy or programmes that are not region specific (Singh and Sureja 2008). Years of harsh climatic conditions have prompted marginal farmers to sustain their own crops using inherited learning and creativity. The TEK based adaptive strategies help build soils that are resilient to droughts and harsh conditions and sustain the cropping systems in an era of drastic climate change (Sharma and Gobi 2016). TEK led adaptations in soil and agro-management help in achieving the long term goal of soil sustainability. As an example the bio-mulching method wherein organic materials are used to cover the soil not only help in moisture conservation in the rain deficient zones but also at the same time enrich soil carbon and reduce crop diseases. The knowledge of these farmers accumulated over generations has helped them to pursue such adaptive practices that are climate resilient, sustainable, cost effective and above all economically feasible (Singh et al. 2014).

Climate change is going to be the biggest threat faced by mankind in the coming decades. Rising temperatures, erratic rainfall and extreme weather is becoming a more common event. Researchers and policymakers are in unison that adapting agriculture to these impacts is a priority for ensuring future food security (Kirsten and Kathy 2013). Strategies to achieve that in practice tend to focus on modern science. But evidence from past and present suggests that the traditional knowledge and crop varieties of indigenous peoples and local communities could prove even more relevant in adapting agriculture to climate change. The Intergovernmental Panel on Climate Change has emphasised on the role of indigenous knowledge and crop varieties in climate adaptation (Parry et al. 2007). TEK is important for environmental change adaptation policies and strategies—when TEK based systems erode, the world loses feasible options to respond to challenges and global environmental change.

20.3 TEK and Adaptive Soil Management Strategies

All over the world, a very large section of traditional farmers and indigenous communities use their traditional knowledge for ensuring food and livelihood security in a large array of ecosystems, especially the fragile and harsh ones. These practices are related to traditional culture and biocultural dynamics and help in regeneration of local food systems and increase socio-environmental sustainability and resilience. Similar adaptive strategies can also be applied in new innovative ways to help tackle today's issues. Through their on-farm/in situ conservation and management of available resources, the farming communities following traditional lifestyles are able to maintain high levels of genetic resources for food and agriculture. This creates an important basis for the food security of present and future generation world over.

Africa, Asia, America, Australia and many other parts of the world have a rich cultural heritage of the indigenous knowledge in agriculture sector. These systems and adaptive methodologies are suited to their microenvironment but have chances of replicability in similar climatic zones.

Traditional ecological knowledge (TEK) is one of the major components of the Globally Important Agricultural Heritage Systems (GIAHS), which are good living examples of evolutionary adapted socio-ecosystems in human history (CelaCruz and Koohafkan 2009). These traditional heritage systems have been passed down for generations to generations, because of their excellent local traditional knowledge and practices. A living example of GIAHS is the 'The Hani Rice Terraces System', located in China's south-western Yunnan Province (Yuan et al. 2014). It has been in existence for more than one thousand years, based on TEK related to cultivation and natural resources management, which was preserved and practiced continually. Over the long time period, TEK has enabled the Hani people to skillfully manage their terraces and other natural resources in a sustainable way (Yuan et al. 2014).

The Maya people of Central America and south-eastern Mexico have adapted an agriculture system known as 'Milpa' (to the field) agricultural systems for almost three millennia (Flores-Delgadillo et al. 2011). The Maya traditionally used the slash-and-burn methods to manage agriculture of variety of species like maize, beans and squash, among other plants for food and medicinal purposes; they also adopted terracing in their agricultural fields and manipulated the wetlands for agricultural production (Flores-Delgadillo et al. 2011). Maya used a different cultivation method that made their agricultural system effective. They used site-specific crop management by planting perennial plants and crops in cavities of limestone bedrock that were filled with soil (Flores-Delgadillo et al. 2011).

In coastal Kenya, sacred forests (or 'kayas') conserve the animal and plant biodiversity and are a valuable source of germplasm for species that are tolerant to extreme weather conditions. Unfortunately, following the 'Green Revolution' and the pressure to use the so-called modern agriculture to improve food production and security, a huge proportion of farmers grow modern monoculture hybrid crop varieties. The studies from China, Bolivia and Kenya all identify and encourage the need to support local initiatives such as community based landrace conservation and local seed production, seed banks and participatory plant breeding related extension activities to increase self-reliance in the resource deprived farming communities world over.

The above-mentioned strategic methodologies suited to varied ethnic groups in different parts of the world have a very strong foundation of living in harmony with the Nature. These systems were not driven by greed but the underlying principle of respect and love for the ecosystem helped flourish man and nature intricately. However, the era of industrial revolution, unprecedented boom in population, replenishing resources and above all the driving greed of man ushered the whole agri-management system into the present state of failure and distress.

India, with its rich cultural heritage,-has enormous knowledge base endowed in the traditional scriptures 'The Vedas and Upanishads'. The Vedas and Upanishads are the collection of knowledge and experiences of the intellectual ancient Indian civilisations. Each hymn in these scriptures has described various diversified aspects of mankind from astrology to spirituality and from medicine to agriculture; all aspects have been covered in a very subtle way and are very much relevant till date. 'Rig Veda and Krushi Parashar' finely describe crops and their cultivation techniques, rain forecasting and soil adaptations. All the diversified aspects related to agro-management techniques have been dealt with detail in these valuable treatises. These ancient goldmines of knowledge have emphasised on the 'Vedic Krishi system' which was practiced by ancient sages since the dawn of agriculture in the evolution history of mankind. The systems explained in detail were all in harmony with nature, with the fundamental governing principle of giving back to the nature what one takes from it. Ever since the dawn of agriculture the farmers impart the Panch sanskars to the agro-ecosystems and hand over to coming generations. These include the sanskars/ rituals for soil, seed, jal (water), vayu (air) and field sanskar. These sanskars are passed down to next generation in the form of folklores, proverbs, rituals and songs. Some of these traditional practices are as follows:

- Achhadana/Bio-mulching: Using locally available organic wastes like leaves of trees or sugarcane trash are a vivid example of how soil can retain the little moisture it receives under harsh climatic terrain.
- Bijamrut: Seed treatment. Prior to sowing; the seeds are treated with organic materials like cow urine and then sown.
- Native seeds and varieties: Local seed banks, production of seeds at local level and participatory plant breeding. Farmers' seed system is an important aspect of adaptation.
- Bioformulations like Jivamrit. A fermented concoction of cowdung, cow urine, jiggery and gram flour along with some soil. The microbial population grows manifold with the availability of carbohydrate (jaggery) and protein (gram flour) and after five days this bioformulation shows wonderful effects on the soil and crops.
- Natural fertilisers/vermicompost.
- Natural pesticides/brahmastra.
- Livestock rearing: the farming communities rear livestock on farms, in general and this livestock is a source of natural composting materials.
- Traditional cropping calendars based on lunar cycle.

20.4 Scenario in the Semi-Arid Tropics: The Kachchh Case Study

The sustainability of agro-ecosystems in resource scarce semi-arid tropical zones is an important issue. A study (Sharma et al. unpublished) was undertaken to find out the role that TEK plays in implementing and imparting this indigenous knowledge in the field of agriculture from generations to generations and how this knowledge forms the very basis of agricultural sustainability. The ancient knowledge of sustainable farming practices of the farming communities in semi-arid tropics is on the verge of being lost. Kachchh is a very unique ecological terrain of Western India where some experimentive and progressive farmers, in-spite of harsh climatic conditions and frequent droughts, have adopted the long lost traditional farming practices (as explained in the above Sect. 20.3) that need to be given a sound scientific backing for making it feasible because synthetic inputs based farming practices are deteriorating the overall soil health and quality of produce.

20.4.1 Geo-Ecological Setting of Kachchh

The Kachchh region is named so because its topography resembles the back of a tortoise, (*kachbo* in Gujarati) with the central portion (near Bhuj) elevated and the land gently sloping downwards from there in all four directions. Due to this sharp gradient all the rivers and streams of Kachchh are non-perennial and have a high run-off rate, therefore agriculture in this area is highly rain dependent, with some exceptions where underground bores are used for irrigation. Kachchh is classified as biogeographic zone "3A" experiencing tropical arid climate (GEC 2011). Kachchh has an area of 45,612 sq. km and is India's second-largest district as it sprawls over 24% of the total area of the western Indian state of Gujarat and stretches between 22°41′ 11″ to 24°41′ 47″ north latitude and 68°09′ 46″ to 71°54′ 47″ east longitude. With a coastline of 406 km boasting nine ports, this area in northwest Gujarat is located in the state's arid tract and seven of its nine talukas are rated drought-prone. The frequency of droughts in Kachchh is said to be once in every 2.5 years. The unique topography of Kachchh compounded with erratic rainfall makes agricultural practices a challenging issue. The availability of both major and micronutrients is often a limiting factor (GEC 2011).

20.4.2 Soil and Agricultural Practices in Kachchh

According to National Bureau of Soil Survey and Land Use Planning (NBSS and LUP circular 2005) the soils in this area belong to great group typic-camborthids. The soils are sandy loams (calcareous). Semi-arid climate with very scanty rainfall does not support extensive and water intensive agriculture in the region. All these conditions have created limitations in agriculture practices in the region. The region naturally does not support water intensive crops and any crop is susceptible to

Table 20.1 Cropping pattern in rain-fed and irrigated agriculture

Agriculture type	Kharif	Rabi
Rain-fed agriculture	Mix cropping of pearl millet, sorghum, castor, sesame, cotton, groundnut, greengram, clusterbean	Castor and cotton grown in kharif are continued
Irrigated agriculture—field crops	Pearl millet, castor hybrid and cotton, groundnut, sorghum	Castor and cotton grown in kharif are continued. Isabgol, cumin, wheat, mustard and vegetables
Irrigated agriculture—fruit crops	Good-quality water—mango, papaya, banana Poor-quality water—date palm, sapota and Indian gooseberry	

Sharma and Gobi (2016)

droughts and high velocity of wind and even cyclones and higher temperature levels. The region possesses soil types ranging from black soil to red loamy soil. The major soil types in the region are red loamy, red sandy, red gravelly, and deep, medium and shallow black soil. Black soil types are mostly concentrated in the southern and western coastal areas, while red soil types are predominant in the northern and eastern belt. Moreover, saline and saline alkali is the basic soil type in the Banni area and in some parts laterite soil is also available. Back soil types and red loamy soil are favourable for various crops from cotton to oil seeds and spices.

Both rain-fed and irrigation based farming systems are prevalent in Kachchh. However, 80% of agriculture is rain-fed. Table 20.1 summarises various preferred crops depending upon the farming system adopted. Kharif is the summer crop while Rabi is the winter crop.

20.4.3 Major Highlights of the Study

A comparative microbial diversity and nutrient availability analysis of TEK based systems versus chemical integrated agri-amendment systems was carried out in the earmarked fields of Kachchh, Western India (Sharma et al. 2014a). The organic farms were subjected to various practices viz: Acchadan, seed treatment, Jivamrit application and use of natural pesticides as ‘Brahmastra’ that are a traditional wealth of the age old ‘Vedic Krishi’ system from ancient India. Whereas the synthetic input based fields were subjected to application of chemical fertilisers and pesticides. Soil sample collection was done from the rhizosphere of the crop up to the depth of 12 cm using standard soil sampling procedure. Samples were analysed in triplicates for physical-chemical characteristics and microbiological analysis. It was observed that organic based farming systems provide the major plant nutrients to the crops at the required timings. The advantages of application of organic amendments are manifold, which include increased organic matter content, improved soil physical and chemical properties and also provision of micronutrients that are seldom applied by farmers (e.g. manganese, zinc and sulphur). Furthermore, nutrients that are usually applied in commercial fertilisers (e.g. potassium) and liming sources (i.e. calcium, magnesium) are supplemented in organic amendments.

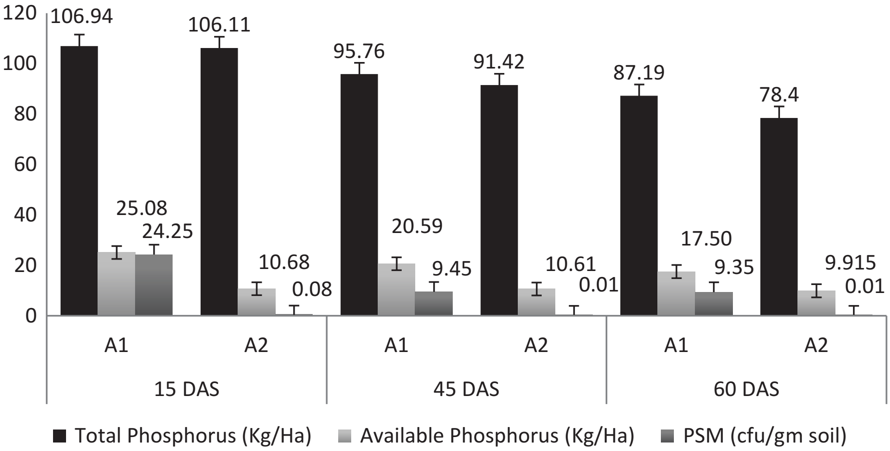

Fig. 20.1 Total phosphorus, available phosphorus and PSM count at 15, 45 and 60 DAS (Sharma et al. 2014a)

Similarly major nutrients that are locked in the soil at the peak crop requirement are made available to the crops by the microorganisms found in TEK based bioformulations. As an example of phosphorus that is abundant in soils in both organic and inorganic forms, however, it is frequently a major limiting factor for the growth of plant as it is in a form that is not available for root uptake due to its fixation in the soils. The soils that exhibit highest P fixation capacity occupy an area of around 1018 million hectares (Ha) in the tropics (Sanchez and Logan 1992). However, the PSM (Phosphate Solubilising Microorganisms) like *Pseudomonas sp., Bacillus sp., Aspergillus sp. and Penicillium sp.* through different mechanisms of solubilisation and mineralisation convert inorganic and organic soil P, respectively, (Khan et al. 2009; Sharma et al. 2014b) into the bioavailable form that the plant roots can uptake. These PSM are found in abundance in soils that have been amended using traditional bioformulations. A study by Sharma et al. (2014a) has shown that at 45 DAS (days after sowing) in the fields with organic amendment (A1) recorded significantly higher available phosphorus ($P \leq 0.001$) than the integrated amendment fields (A2) which also coincided with the higher population of PSM in A1 (Fig. 20.1).

Study (Sharma et al. 2014a) was undertaken to assess the role of NRI (Natural Resource Integration) in ecosystem sustainability. The results have shown that agri-management systems need to be geared to more inputs of traditional practices that use organic pesticides and manures, bioformulations prepared using TEK, indigenous seeds, best suited for the native climatic conditions, which can help in long term sustainability of the agriculture. The organic input based amendment systems were able to maintain a good microbial count (total as well as Phosphate Solubilising Microorganisms), nutrient index and physical attributes like the water holding capacity, etc., as compared to integrated fields. This is in confirmation of the fact that efficient nutrient management in agri-management systems could gear up microbial population which in turn helps solubilise the fixed nutrients and make it available to crops. Hence such systems are important aspect of adaptive soil management strategies.

20.5 Conclusions and Future Directions

Agro-ecosystem sustainability in semi-arid tropics is an important issue. The age old TEK based agriculture resource of our country not only has an answer to the crucial situation of the resource poor farmers, but also can sustain our ecosystem health in the long run. This enormous indigenous knowledge needs to be given a sound scientific backing for rendering it feasible in semi-arid tropics. India and many developing countries have a rich cultural tradition of their own. The so-called progressive agriculture that relies on high yielding hybrid varieties of crops and ever-increasing and indiscriminate doses of chemical fertilisers and pesticides have crippled the whole food system and harshly uprooted the time honoured agro-management practices. Before this enormous wealth of TEK in the agri- sector is lost forever, the scientists and researchers should learn, systematise and try to give it a scientific beckoning, given that these practices are rapidly replenishing due to socio-economic and political pressures. Erosion of cultural systems due to modernisation, weakening of traditional resources and authorities coupled with governmental policies promoting modern techniques at the expense of indigenous knowledge based practices have been instrumental in the decline of the TEK based agriculture systems.

The policy makers and planning commission can be geared to promote farming systems based on natural inputs in these areas. An effective coordination of science and TEK is the need of the day. On the practical side, traditional knowledge has a strong foundation but sometimes has a weak theoretical basis, making it difficult for it to be applied more widely. The natural systems have been deeply impacted by agricultural policies, subsidies and research that promote modern varieties and technologies at the cost of deterioration of indigenous knowledge and biodiversity. Existing practices which are beneficial, but are on the verge of being lost in a rapidly changing world, can be protected if the planning commission and policy makers can reinforce them and relate them to the growing population. Agri-management systems need to be geared to more inputs of traditional manures, pesticides and practices like indigenous seeds, mulching, best suited for the native climatic conditions, which can help in long term sustainability of the agriculture, soil and the society. The enormous wealth of TEK needs to be given a scientific beckoning in the form of concrete research. The precious knowledge database should be well protected from infringement through Intellectual Property Right (IPR). Modern methods of agriculture should be a support system for the traditional knowledge based farming and not overshadow it. TEK based systems should be an important part of adaptive soil management strategies that advocate the sustainability of the ecosystems in the long run.

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The Effects of Forest Fire on Soil Organic Matter and Nutrients in Boreal Forests of North America: A Review

21

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Abstract

Fire is the primary disturbance process affecting the structures and ecosystem functions of a forest by altering the carbon balance and nutrient dynamics of forest soils. A great deal of research indicates that frequency, severity, duration of forest fire will increase especially in boreal forest region with the increase in temperature and severe droughts resulting from climate change. However, with the large area and abundant biodiversity, boreal forest plays a vital role in mitigating climate change and acting as a carbon pool. Therefore, if the boreal forest is damaged by fires, it will incur a catastrophe on the ecosystem and the climate. With increasing risk of future fire activities, it is extremely important to understand the dynamic changes of soil resources as affected by fires which can give a crucial information on sustainable and adaptive management practices of forests and soils, as well as determine the resilience of forest soils to mitigate current climate change. In this paper, we review the main fire regimes and characteristics of boreal forests in North America and the dynamics of organic matter and nutrients in forest soils over short and long-term after fire. This work aims at providing useful knowledge on soil resource dynamics under fire disturbance which will further promote the adaptive management of forest soils.

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21.1 Introduction

Boreal forest covers about 1.2 billion ha area and accounts for 30.6% of global forest cover (FAO 2015). It plays an essential role in ecosystem biodiversity, climate regulation, carbon storage, and biogeochemical cycling in the northern circumpolar region. About 30% of the global boreal forest is widely distributed in North America covering from Alaska to Newfoundland, while the remaining is known as the Taiga in Eurasian spreading over Russia, Sweden, Finland, and Norway (de Groot et al. 2013). The tree species commonly found in boreal forests are white spruce, black spruce, tamarack, jack Pine, and Balsam Fir (Rowe and Scotter 1973). Based on the weather conditions and soil types, boreal forest eco-zones in North America are generally divided into eastern and western boreal forests. Podzol is the dominant soil type in eastern boreal forests with the relatively humid weather while Luvisol and Brunisol are the dominant soils in the western boreal forests with dry weather (Maynard et al. 2014). These inherent soil properties greatly influence the plant growth by providing nutrients and physical support. Due to the cold and dry weather condition, soil is characterized by the low decomposition rate, nutrient limitation, and accumulation of soil organic matter (SOM) in the boreal forest region of North America. Fire is the most significant disturbance driver that promotes the forest dynamics and nutrient movements in boreal forests (Hansen et al. 2013). It substantially changes the structures, composition, and ecosystem function of a forest, as well as carbon balance and nutrient dynamics (Fregeau et al. 2015). The effect of fire on soil properties relies heavily on the fire regime (e.g., fire intensity, fire severity, type of fire, fire season, fire size), vegetation type, and climate conditions (Gill and Allan 2008). Fire intensity is an intrinsic attribute of fire that is defined by the heat energy or thermal energy released per unit time per unit area (Keeley 2009). Fire severity or burn severity, described as ecosystem responses to fire disturbance, is influenced by both intensity and duration of fire and operationally classified as low, moderate, and high (Bento-Gonçalves et al. 2012). Fire types include surface fire, ground fire, and crown fire, which are determined by fuel types and fuel loads supplied by different forest tree species. A boreal forest fire is dominated by intensive crown fires from higher forest floor fuel loads, and results in a higher carbon emission rate (Stocks et al. 2004). The fire season of boreal forest spans April to August with large wildland fires predominantly occurring in the month of June and July in northern and remote areas of the boreal forests initiated mainly by the natural factor—lightening (Stocks et al. 2003). In addition, human-induced factors take responsibility for a small portion of fire activities which are basically observed in the southern areas of boreal forests in the spring and fall (Stocks et al. 2003).

Furthermore, the cold and dry fire weather and coniferous-based vegetation type (pine, spruce, and aspen) contribute to the unique fire regimes in boreal forest regions differing from other forests. Reversely, vegetation types and forest structure are reshaped and adapt to fire regime, by putting up with burning, survival, and regeneration. In essence, boreal tree species and fire regimes are interactively affected.

With the present climate change, the enhanced temperature and severe droughts exposed forests to increased fire risks and will further exacerbate the fire disturbance in the near future (Girardin et al. 2010). Especially, the recent prediction emphasized a potentially significant increase in fire frequency, fire length, and burned area in the circumboreal region as a drastic decrease of fuel moisture due to global warming (Flannigan et al. 2013). Yet, with a large area and abundant carbon storage, boreal forest plays a vital role in mitigating climate change and storing carbon. Therefore, once damaged, it will incur catastrophe on the ecosystem. Increasing risk of future fire activities and unprecedented challenge in boreal forests will infer direct and indirect impacts not only on vegetation, but also on forest soil with regard to SOM, macro and micro-nutrients, and physical properties such as soil color, bulk density, soil texture, and soil structure (Verma and Jayakumar 2012). The response of forest soil to fire disturbance determines the carbon loss, dynamics, and availability of nutrients as well as post-fire regeneration of vegetation to a large extent. Furthermore, empirical knowledge of the dynamic changes of soil and the interactions with disturbance agents are increasingly important and provide a crucial information on identifying sustainable and adaptive management decisions of forest and soil (Brandt et al. 2013).

The main objective of this paper is to bring together studies of dynamics of organic matter and nutrients in forest soils over a short-term or long-term after fire disturbance, and present the latest advances in the adaptive management regarding the reliance of soil, with a specific insight on the boreal forest soil in North America.

21.2 Fire Effects on Soil Organic Matter

Soil organic matter (SOM) is important in maintaining ecosystem functions. It forms soil aggregates, builds soil structure, absorbs and releases soil nutrients, holds water, regulates carbon cycle, and supports biological diversity. Boreal forest as one of the world's largest and most important biogeoclimatic area plays an important role in carbon budget as a large amount of carbon is stored in aboveground vegetation, forest floor, and organic and mineral soil horizons. Fire is a major driver of the carbon balance by release to the atmosphere from combustion during the fire and several processes of carbon dynamics following fire (Amiro et al. 2009). As direct assessment of effects of fire on forest soil is rare due to lack of reliable pre-fire data (Bormann et al. 2008), most of the present research are conducted in comparison of burned site and nearby unburned site.

21.2.1 Quantitative Changes

The impacts of fire on SOM are highly dependent on fire intensity, soil moisture, climate, and vegetation (Caon et al. 2014; Nalder and Wein 1999). However, the most intuitive and common change of soil after the fire is the loss of SOM (Certini 2005). The forest floor is recognized to contain more than half of the total stand biomass of forest and transformation of SOM mainly happens in forest floor rather than mineral soil horizons. Poirier et al. (2014) synthesized the effects of 14 low-severity fires from 2005 to 2007 in boreal forests in Quebec, Canada and reported that the amounts of SOM in the organic horizons and surface mineral soil layers (0–15 cm) were reduced by 7 and 20%, respectively, without reducing anything in the subsurface mineral horizons (15–40 cm). Though the reduction percentage was more significant in mineral surface soil layers, the total SOM in surface organic horizons was 20 times higher compared to the mineral horizons. The vertical distribution of SOM for a soil profile is not uniform, and usually displays an exponential decay tendency (Minasny et al. 2006). In addition, the loss of SOM varies across different depths of soil profile due to the heat loss when transferring down a profile and different fire severity along depths (Page-Dumroese and Jurgensen 2006). Even though a severe fire with the highest temperature of 1000 °C destroyed all the aboveground vegetation and left only 9–21% of the original amount of SOM in the organic horizons, the SOM content in the mineral soil horizons (2–42 cm) did not change (Smith 1970).

Moreover, the effects of forest fires gradually decrease over time since fire. Though the carbon loss is compensated to some extent by regeneration and recovery of the forest vegetation, the pre-fire carbon content could not be achieved even after quite a long period of time. In order to examine the effect of time since forest fire, researchers compared the immediate and long-term effects of fire on soil carbon dynamics. Norris et al. (2009) compared the response of SOC content at 4, 29, and 91 years following disturbance and reported a drastic carbon loss at 4 years after the fire, while gradually rising again over a long period (SOC from 2% after 4 years to 33% after 91 years for forest floors). Similar results were also reported by Kishchuk et al. (2014a) after comparing short-term (2 months) and long-term (10 years) responses of SOM content from fire disturbance. Simard et al. (2001) also reported the time effect since forest fire by comparing SOM content at 2, 14, and 21 years after the forest fire in the eastern boreal forest. Though the western boreal forest experiences relatively dry weather condition, Nalder and Wein (1999) still illustrated consistent SOM dynamics when measuring 14–149 years' forest floor carbon dynamics after the fire in Saskatchewan, Alberta, and Manitoba provinces in Canada.

21.2.2 Qualitative Transformation

As for the qualitative change of SOM, the most common transformation is the formation of carbon dioxide (CO_2). Additionally, methane (CH_4), carbon monoxide (CO), and aerosol black carbon are some other common gaseous forms of carbon emission from a forest fire. Martin et al. (2006) observed a significant increase of aerosol black carbon from Boreal outflow and an increase of CO emission from fire and reported a strong correlation between CO emission and aerosol black carbon. de Groot et al. (2013) discovered a higher carbon emission rate in western boreal forests due to the dominantly intensive crown fires, sufficient forest floor fuel supplied by large carbon pool, and dry soil and weather conditions, compared to Taiga in Eurasian.

Apart from a large amount of gaseous carbon, fire can also produce pyrogenic carbon, also called black carbon when the burning temperature is above 250 °C, a primary by-product of wildland fire in boreal forests (Soucemarianadin et al. 2015). Pyrogenic carbon is a stable and recalcitrant product produced from fast or slow pyrolysis in the absence of oxygen with the process of dehydration of hydrocarbons, and aromatization of carbon (González-Pérez et al. 2004; Page-Dumroese and Jurgensen 2006). Pyrogenic carbon is made up of aromatic carbon, phenolic carbon, carbonyl carbon, and alkyl carbon. The contributions of each of these components on the structure of the pyrogenic carbon products are determined by the moisture condition, maximum temperature, and duration of charring (Rutherford et al. 2005). Among others, aromatic carbon is the most stable form and determines the recalcitrance of pyrogenic carbon, thus being regarded as a major component of stable carbon pool in soil (Soucemarianadin et al. 2015). Soucemarianadin et al. (2015) analyzed samples from eastern boreal forests which went through low-intensity smoldering fires due to humid weather condition with temperatures ranging from 75 to 250 °C and observed incomplete burning products with a lower amount of aromatic carbon. This shows that pyrogenic carbon in boreal forests is displaying different characteristics (low in aromatic structures and unstable) compared to other forest ecosystems, such as Taiga in the Eurasian and the forests from Mediterranean region. Norris et al. (2009) discovered the presence of a large amount of aromatic C in forest floor 4 years after the fire, while over a long-term, more O-alkyl content was observed for soil samples at 29 and 91 years after the fire in boreal forests in Canada. In addition, an increase of aromatization was also observed with increasing fire severity in that study.

21.2.3 Inherent Processes

The SOM losses, ramping up over a long-term, and transformation of structure and composition, are all owing to the inherent physical (translocation), chemical (transformation), and biological (decomposition) processes operated under fire.

The short-term reduction of SOM is due to the chemical transformation to gaseous forms and subsequent emission and volatilization of the gaseous products, mainly caused by direct combustion at the forest floor. Other products of chemical transformation are pyrogenic carbon or more recalcitrant black carbon, which is less vulnerable to further abiotic and biotic decomposition and serve as long-term soil carbon pool (Buma et al. 2014). The combustion and heat reduce the activity of microbial community and hence the decomposition of SOM by microorganisms.

Actually, debris and residues of burned plant materials have already destroyed the original structure that serves as a positive source for accelerated breakdown and decomposition by microbes. In addition, the decomposition process can also be substantially accelerated with the change of microclimate and increased daytime temperature influenced by less vegetation cover after fire (Certini 2005). The destroyed soil structure and bare soil surface make it difficult to protect soil particles and nutrients from rainfall, water and wind erosion, surface runoff, and leaching, which can cause a large amount of loss of SOM in the following years after fire. Especially in the boreal forest region, the microbial activities are increased following fire compared to that in pre-fire cold weather condition. However, Norris et al. (2009) observed a translocation of char from the forest floor to the mineral soil layers, which substantially increased SOM content in mineral horizons, and kept SOM stably stored and mitigated the large carbon emission in the long-term. In the long-term, the burning effect will gradually weaken and carbon stock will ramp up due to the regeneration and recovery of forests (Caon et al. 2014).

21.3 Fire Effects on Plant Nutrients

21.3.1 Nitrogen

Nitrogen (N) is an essential macronutrient for plant growth and is present in the soil in two forms: organic N and inorganic N. Organic N roots in decomposition process of debris and secretions from plants and animals, or nitrogen fixation process by acetobacter or lightening fixation from gaseous N_2. Basically, organic N exists in the complex organic compound and is unavailable for plant uptake. In order to transform organic N to an available form of nutrient that plant can take up, it has to go through several chemical and biological mineralization processes (ammonification) which produces NH_4^+. Except for NH_4^+, NO_3^- and NO_2^- are another two forms of nitrogen that can serve as plant nutrients, and the corresponding nitrification process and denitrification process are two integral components of the complete nitrogen cycle (Fig. 21.1) (Lupi et al. 2013). Furthermore, in the low-oxygen soil environment, NO_2^- is further denitrified to N_2 and finally released to the atmosphere. Therefore, when discussing the nitrogen dynamics after the fire, the whole nitrogen cycle processes and different forms of nitrogen should be carefully considered. Due to the cold weather, a particular characteristic of the boreal forests, the microbial activities, decomposition process, and N cycle slow down and cause N-deficiency problem to the forest vegetation (Rowe and Scotter 1973). With a high amount of unavailable organic N, the forest fire provides a chance that promotes the transformation of organic N, accelerates the N cycle, and provides more nutrients for plant growth.

Similar to SOM, when forest fire occurs, a significant decrease of total nitrogen was observed mainly on the forest floor without extending to mineral horizons. However, the N content gradually increased over the long-term (after about 100 years)

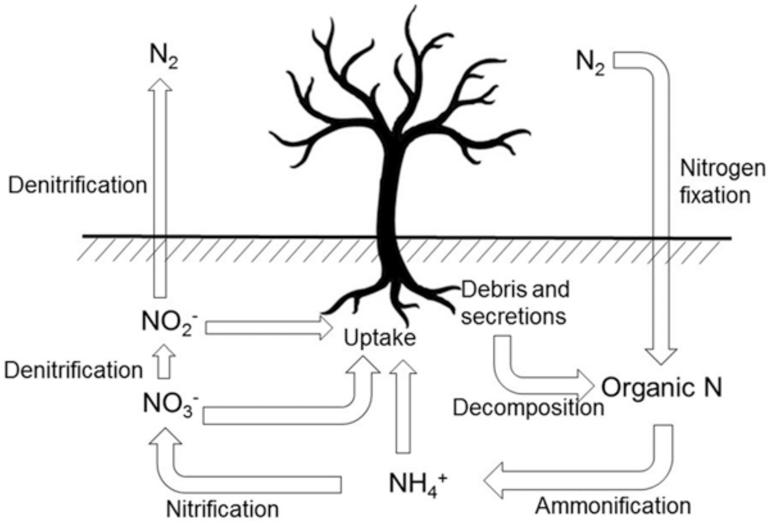

Fig. 21.1 A simple diagram of transformation processes of nitrogen in soil. The arrows represent the transformation processes, including nitrogen fixation, decomposition, ammonification, nitrification, denitrification, and uptake by plant. The elements indicate the products of the transformation processes, including N_2, organic N, NH_4^+, NO_3^-, and NO_2^-

(Maynard et al. 2014). As expected, the available nitrogen (NH_4^+ and NO_3^-) increased following fire (DeLuca et al. 2006). An immediate increase of extractable NH_4^+ was observed by Wan et al. (2001) after the fire in boreal forests due to the ammonification and release from organic matter. Though the NO_3^- was not immediately altered by forest fire due to the delayed transformation process of nitrification (Kishchuk et al. 2014b), it increased 10 years after the disturbance.

Generally, forest fire enhanced the local temperature, and destroyed undecomposed organic matter into debris, resulting in an increase of microbial activities and underlying mineralization processes in the nitrogen cycle. Another two processes, volatilization and leaching contribute to the loss of nitrogen. The volatilization rate of N depends on the temperature of the fire and the evaporating temperature of organic N is around 400–500 °C. According to Gray and Dighton (2006), when the fire is lower than 100 °C, the topsoil lost 15% of the total N and about 35% of the total N loss occurred at 250 °C. As fire reached to 350 °C, only 30% of the total N remained on the top surface of the soil. In addition, the moisture content of the soil can affect the degree of volatilization. The higher the soil moisture content, more water is stored in the soil pore. When a fire occurs, the water will absorb the thermal energy from the fire. Therefore, higher temperature is needed for the occurrence of volatilization inside the wet soil (DeBano 2000). Leaching, another process that can loose soil N, does not happen right after the occurrence of the forest fire and only take place after a period of time. As NH_4^+ is a short-lived intermediate product which will eventually convert into NO_3^- by nitrification, the main component of the lost N is NO_3^-. Murphy et al. (2006) observed an increase of concentrations of NH_4^+, NO_3^-, and ortho-P in the seepage of burned area. Since the fire destroyed the forest structure and the aboveground vegetation and coverage, the bare ground could not protect nitrate from runoff and leaching. In addition, the altered SOM structure and reduced surface area and porosity cannot absorb nitrate, thus exacerbating the nitrogen loss. Leaching process predominantly affects the loss of forest nutrients in the early spring due to snowmelt (Rowe and Scotter 1973).

21.3.2 Phosphorus

Phosphorus (P) is another essential major nutrient required for plant growth and is available through phosphate (PO_4^{3-}). One of the obvious conversions during the fire is that the organic P will go through mineralization and form orthophosphate which can be absorbed by the plant (Cade-Menun et al. 2000). In addition, an increase in soil pH is responsible for the conversion, though the effect does not last long (Certini 2005). In addition, the pine residues in the boreal forest could provide the high amount of orthophosphate at around 70 °C, and the supply would decrease once over the temperature due to the formation of organic more complex organic compound, reflected by the increase of ratio of organic P and orthophosphate (Gray and Dighton 2006).

Maynard et al. (2014) noticed that plant available P increased after fire disturbance. However, Smith (1970) elucidated that extractable P decreased immediately after the fire, and continued to decrease in the following sampling dates (maximum 3 months) in L–H horizons in Ontario boreal forest. In addition, a downwards movement was observed in this study that with the decrease of extractable P in L–F horizons, an increase of P was observed in 0–12 cm mineral horizons; moreover, with the decline of extractable P in 0–12 cm mineral horizons 5 weeks after the fire, an increase was followed by 28–42 cm mineral horizons. Similarly, Kishchuk et al. (2014a) reported that the extractable P significantly declined by 44.2% compared to control treatment on the forest floor, while it greatly increased by 102% in mineral soil horizons. In the long-term, the extractable P was often lower than the initial level (Shrestha and Chen 2010).

P is a very stable element that is not easily disturbed by the outside environment. Unlike N, P has a high volatilization temperature point of around 1400 °C (Pike 1930), which is difficult to reach by fire ensuring minimal P loss from volatilization (Certini 2005). However, in reality, P could still be volatilized in a small amount and blown away by the wind with ashes after the forest fire (Gray and Dighton 2006). Leaching is another important factor that is responsible for the P loss, especially in the eastern boreal forest, where P deficiency and groundwater eutrophication are serious agricultural, forestry, and environmental issues.

21.3.3 Base Cations

Different behaviors of exchangeable cations were observed by different people in forest fire research. Maynard et al. (2014) found that there's no change of exchangeable K in the forest floor after a fire in the Boreal Forest, but significantly higher concentration was observed in the mineral horizons. They also reported a higher amount of exchangeable Ca and Mg in soil following the fire. However, Murphy et al. (2006) compared pre- and post-fire soil properties and found a significant decrease of K, Ca, and Mg at 53, 90, and 90%, respectively, in the forest floor following wildfire. Authors also observed a slight but nonsignificant increase of Ca and no changes of K and Mg in mineral soils. Johnson et al. (2014) compared pre- and post-fire cations and found that Ca increased after a fire and persisted for 2 years. Exchangeable K and Mg were not significantly affected by burning. Kishchuk et al. (2014a) studied a severe fire behavior and stated an increase in exchangeable K both in forest floor and mineral soils immediately after the fire and then a decrease after 10 years of recovery. Exchangeable Ca displayed an opposite behavior whereas Mg decreased at the beginning and kept consistent over 10 years. Simard et al. (2001) observed an increase of exchangeable Ca and Mg both in forest floor and in the mineral soils in the youngest burned stand. They also observed a significant increase of exchangeable K only in the mineral soils, while no significant difference of exchangeable K in the forest floor. Neff et al. (2005) observed a moderate to severe fire and found no statistically significant changes in Ca, K, and Mg. Above all, different behaviors were elucidated, though, there are still similar dynamic patterns of cations, and this is the case of the trade-off between input from burning products, redistribution along soil profiles, as well as output due to loss process.

The increase of exchangeable cations in forest floor following fire is mainly due to the release of ions from the combustion of aboveground vegetation and soil organic matter. Afterward, the cations are redistributed by downward leaching and an increase of cations in mineral soil is observed. However, K is more mobile compared to Ca and Mg and is easily translocated to the subsurface and higher K concentration was observed in mineral soil (Maynard et al. 2014). Likewise, Smith (1970) explored the behavior of K, Na, and Ca after a severe fire in the eastern boreal forest and illustrated different leaching behavior for specific cations due to the different adsorption properties; more K was leached compared with Ca.

Unlike N and P, K is less volatile unless the burning temperature higher than 774 °C. Ca and Mg are also non-volatile elements and the loss is minimal (Maynard et al. 2014). However, soil erosion and deep leaching are the main causes of the loss of exchangeable cations, and a lot of nutrients were leached away immediately after fire due to the increase of solubility. In addition, fire destroys soil structure and bare the soil surface, making it more vulnerable to water and wind erosion. In addition, destruction of SOM structure reduces its exchange capacity and absorbability, which exacerbate the loss of nutrients. In the long-term, recovery of forest and vegetation causes uptake of available nutrients from the soil, which will result in a further reduction of soil exchangeable cations.

The fire severity greatly influences combustion degrees of organic matter and control ion release processes. For example, some immediate fire impacts are restricted to the surface soil horizon and have little effect on deeper mineral soils (Neff et al. 2005). Furthermore, fire severity also influences soil destruction degrees and soil structures which impact leaching capacity. Therefore, fire can easily alter the distribution of nutrient concentration through the soil profile (Neff et al. 2005).

21.4 Conclusion

Forest fire makes a great difference on dynamics of soil organic matter and nutrients of boreal forest in North America. Soil organic matter decreases drastically from the combustion and emission during the fire and then gradually increased with the recovery of vegetation. Due to the cold and dry weather in the boreal forest region, nitrogen and phosphorus deficiency is a major issue for plant growth. However, forest fire promotes the conversion and release of inorganic forms of nitrogen and phosphorus from plant debris and organic matter. In addition, an increase of the concentrations of other base cations including K, Na, Ca, and Mg was observed to some extent initially. However, the translocation and immediate or subsequent loss processes take part in the concentration and function of the SOM, nutrients after the fire in the long-term.

Generally, the mineral soils are exposed following fires from lack of vegetation coverage. The fire also enhances the formation of hydrophobic layers which restricts the infiltration of water. These processes increase the loss of nutrients from the wash away with water flow and result in the nutrient-limiting situation for plant recovery (Neary et al. 2005). Soil erosion is a major problem after fire disturbance. Ash is easily blown away by the wind and dissolved nutrients are washed away by the water, resulting in a severe drop of nutrients. In addition, downward leaching not only redistributed the nutrients in soil profiles but also promoted the nutrients and cation loss into groundwater, leading to the eutrophication issue.

Considering all the transformation and movement processes of SOM, nutrients, and cations, as well as the subsequent environmental, agricultural, and economic issues, sustainable management should be carefully decided to adapt the situation. Unreasonable soil and forest management may deteriorate the environment and enhance the soil erosion. Many attempts have been made to restore soil structure and forest ecosystem. For example, salvage logging as an artificially complemented disturbance after forest fire makes a big difference on the soil properties and is regarded as possible post-fire management. Kishchuk et al. (2014a) reported that post-fire salvage logging promoted the increase of soil properties over a long-term (10 years). Furthermore, Poirier et al. (2014) demonstrated that salvage logging for burned area increased the mobility of dissolved organic carbon and nitrogen nutrients, and stabilized and fixed carbon and nitrogen at subsurface mineral soils.

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22 Climate Mediated Changes in Permafrost and Their Effects on Natural and Human Environments

Mi Lin and Asim Biswas

Abstract

Permafrost is one of the major sink of terrestrial carbon. However, the changing climate exerts an enormous pressure making the permafrost a potential source that can emit carbon to atmosphere. This review covers main concepts of permafrost and discuss in depth about the interactions between permafrost and other natural systems under the scenarios of climate change. The main attention focuses on the northern circumpolar where nearly 25% of the land mass is covered by continuous or discontinuous permafrost and is undergoing a tremendous change. Human reaction plays a crucial role in this race between carbon control and warming planet. Anthropogenic activities will thus be taken into consideration in this regard. The purpose of this work is to finally give a clear knowledge scheme on current situation of permafrost and its study frontier in terms of climate change and adaptive management. Future directions of related research will also be suggested.

Keywords

Active layer • Carbon sink • Anthropogenic effects • Climate change • Adaptive management

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22.1 Introduction

In the past 30 years, northern circumpolar zone as well as the high-latitude regions of the Earth has witnessed the rising temperature with an average value of around 0.6 °C for every 10 years (Schuur et al. 2013). The rising temperature may not only lead to the thawing of ice sheet and frozen ground, recent researches have also revealed its great potential in releasing carbon, which deteriorates the greenhouse gas effect. It is commonly acknowledged that permafrost, which stores remnant of the animals and plants for thousands of years, functions as a major sink for terrestrial carbon, twice as much as those stored in the atmosphere (Romanovsky et al. 2001; Schuur et al. 2008; IPCC 2014; Romanovsky et al. 2015).

The northern circumpolar permafrost zone stores an estimated 1700 gigatons of carbon. This so-called permafrost carbon refers to the entire soil organic carbon, including organic soils, mineral soils, peatlands, and soils of the active layer that thaws seasonally (Schuur et al. 2013). Therefore, the northern circumpolar permafrost zone is an arousing concern of researchers as well as communities due to its great potential and enhanced tendency to release great amount of carbon including clean energy resource like CH_4, which may induce countless loss in economy and inevitable degradation on climate change.

Despite that rising attention has been drawn with indication of the increasing literature, complex relations on the interactions between permafrost and the change of its surroundings require a synthetic and clear scheme to clarify. How will the air temperature affect the thawing permafrost and its corresponding boreal? How much and how fast will this huge sink release the carbon and to what extent will it affect the Earth? Whether it is still opportunistic to control the speed from exacerbating the current situation or this negligible release, if keeping the trend, will definitely cause a great loss that we can never reclaim?

Thawing of permafrost causes carbon release through the deepening of the active layer (O'Connor et al. 2010). The active layer, which is the upper portion of soil that thaws each summer, deepens successively as a result of climate change (Tarnocai et al. 2009; Lawrence and Slater 2005; O'Connor et al. 2010). Increasing active layer depth is associated with wetter soil conditions (Christensen et al. 2004). Under climate change, thawing is enhanced in the summer and refreezing is reduced in the winter (O'Connor et al. 2010). A greater active layer thickness can also potentially increase soil water storage and stimulate the formation of talik, a residual unfrozen soil layer with above-freezing conditions favorable for decomposition (Lawrence and Slater 2005; Schuur et al. 2008).

Ecosystem energy balance can also change, altering regional climate and impacting the rate of permafrost thaw and carbon fluxes (Schuur et al. 2008). Changes in primary production and plant species composition, fire frequency, and amount of snow and length of snow season can all be involved in feedbacks. For example, all of these can cause changes in albedo which results in shifts in soil surface temperature (Schuur et al. 2008).

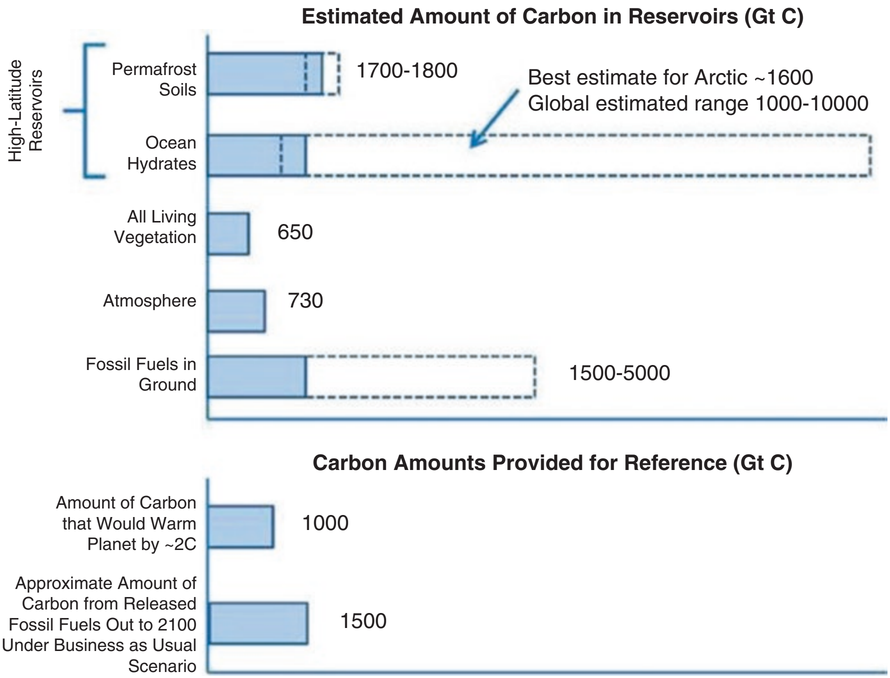


Fig. 22.1 Top: Approximate inventories of carbon in various reservoirs. Bottom: estimated amount of carbon that would warm the planet approximately 2 °C and estimated total amount of carbon to be released by the year 2100 under business-as-usual scenarios (White et al. 2014; Allen et al. 2009; IPCC 2007)

Permafrost soils in the Arctic have been thawing for centuries, reflecting the rise of temperatures since the last glacial maximum (about 21,000 years ago) and the Little Ice Age (1350–1750). However, this Holocene thawing has accelerated in recent decades, and can be attributed to human-induced warming. Under business-as-usual climate forcing scenarios, much of the upper permafrost is projected to thaw within a time scale of about a century (Lawrence and Slater 2005). Exactly how this will proceed is uncertain. The rate of carbon degradation increases nonlinearly with temperatures above the freezing point of water. Furthermore, the spatial pattern of this degradation is spatially heterogeneous owing to small-scale geomorphic processes such as thermokarsting and slumping from ice-wedge melting (Jorgenson et al. 2006). Thus the melting of permafrost could very likely be a climate "tipping point," pushing climate change forward through strong mechanisms of positive feedbacks (Fig. 22.1).

The purpose of this review is to overview and explore the existing literature and body of knowledge regarding the relationships and interactions between permafrost, climate change, and the surrounding environment so as to provide a clearer scheme for further research in the management of frozen soil.

22.2 What Is Permafrost?

22.2.1 Background

22.2.1.1 Definition of Frozen Soil and Permafrost

Literally, the permafrost means permanent frozen. Other alternative description of this process is geocryology, meaning earth cold study and periglacial, meaning near glacier. Despite that people may tend to use this word as a catch-all term to describe all aspects of frozen or nearly frozen ground. A commonly accepted definition of permafrost is that it is a frozen ground which has a temperature lower than 0 °C (32 °F) continuously for at least two consecutive years. The longevity can range from several years to thousands of years. It has covered nearly a quarter of the entire northern hemisphere (Lawrence and Slater 2005). Along with sub-zero subsurface soil temperature, permafrost also refers to a variety of underground materials including mineral and organic soil, rock, and ice (Schuur et al. 2008). It is also called permanently frozen ground, which generally forms in the higher latitudes.

When the word "frozen" has multiple meanings like turning into ice and absolutely still, the meaning adopted to the "frozen ground" is only the former one. In fact, frozen ground does move a lot. They flow, expand, contract, and the soil particles held by them also will shift and deform. You can surprisingly find the freezing ground shrink and swell up like a balloon, or a child with changeable mood. These sub-zero soils of the planet possess unique characteristics and qualities that allow them to store and circulate an astounding amount of carbon throughout their systems when water is one of the main directors of this lively behavior. We can take a glimpse of what is inside the permafrost in Fig. 22.2. It shows the geology of cross section of the Yukon-Tanana Upland, which is bounded by the Tanana River Valley and eastern Alaska Range foothills to the south and by the Yukon River Valley to the north. The asterisks in the profile mark the carbon dating samples from which you could recall how long it has existed. For example, the second asterisk from the top was dated to about 8500 years before present. From this drawing, you can see active layer on top from 0′ to 2.3′ and color transition from yellow to reddish brown to brownish gray and finally to the clear white ice. The richness of fibers indicates the large volume of carbon stored in the soil underground, and the ice content indicates the moisture content pattern and the thawing and freezing processes of the soil profile. For example, the segregation ice in the middle of the profile from 28′ to 29′ indicates that the sub-zero water moved into the porous medium with the presence of ice and then froze to grow the ice extent. The name of the segregated ice just derives from the fact that where water starts off widely dispersed within the porous medium, it becomes segregated into discrete pieces of ice in the form of lenses, ribbons, needles, layers, or strands of ice (Ozawa and Kinosita 1989).

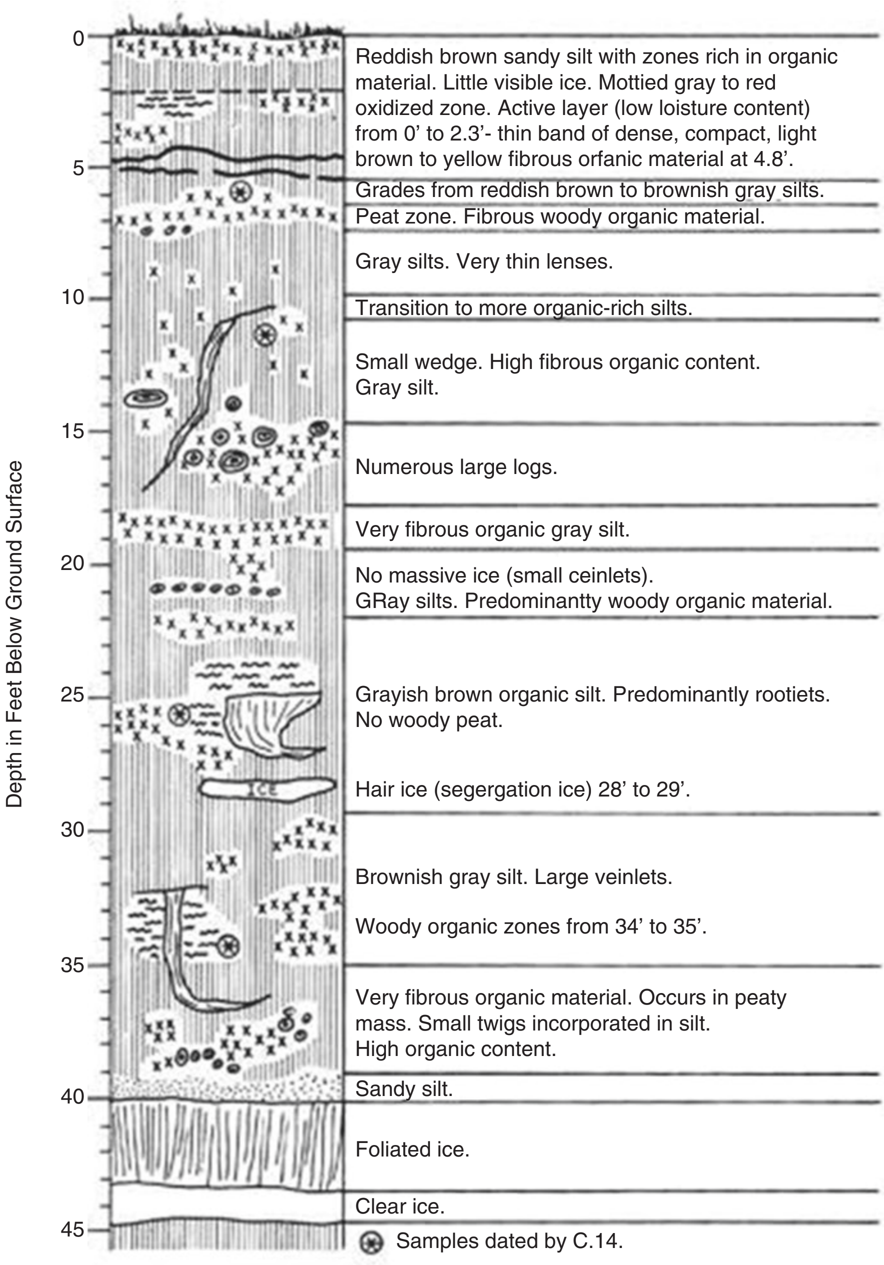


Fig. 22.2 A typical soil profile of the permafrost from the Yukon-Tanana Upland (Sellmann 1967)

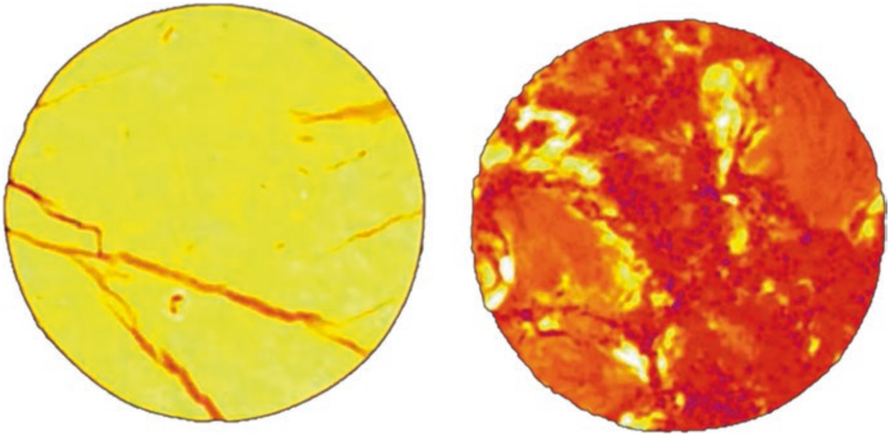


Fig. 22.3 CT scan of active layer and permafrost layer (Resource from Lawrence Berkeley National Lab)

22.2.1.2 What Makes Permafrost Change

Three Layers of Permafrost

To understand the effects of permafrost on a global, long-term scale, it is important to understand the current structure and functions of permafrost. Permafrost is structured in a way that can be divided into three distinct layers, each with distinctive characteristics. The active layer, the uppermost part of the permafrost profile, is the layer that undergoes thawing and freezing. The active layer influences plant rooting, hydrological processes, and the amount of organic material available for decomposition. Underneath the active layer is the transitional zone, an ice rich layer that separates the active layer from the final, underlying stable layer. The stable layer is the layer in which permafrost is permanently frozen and does not undergoes free-thaw changes throughout the seasons. Up to 80% of the permafrost soil volume can be ground ice, therefore a stable layer is necessary for maintaining topography and surrounding ecosystems (Schuur et al. 2008).

Lawrence Berkeley National Lab innovatively used the CT scan to look for the details of the core of permafrost. Figure 22.3 shows the cross sections of active layer and permafrost layer. In the left bright circle where the active layer displays, we can see the thin veins of ice represented by the red slashes while the red moving dots represent the plant roots. In the right circle is the permafrost layer where the orange is ice and the dark dots are gas bubbles.

The Scenarios of Climate Change-IPCC

Climate change refers to a change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer (IPCC 2014). Climate change may be due to natural internal processes or external forcing such as modulations of the

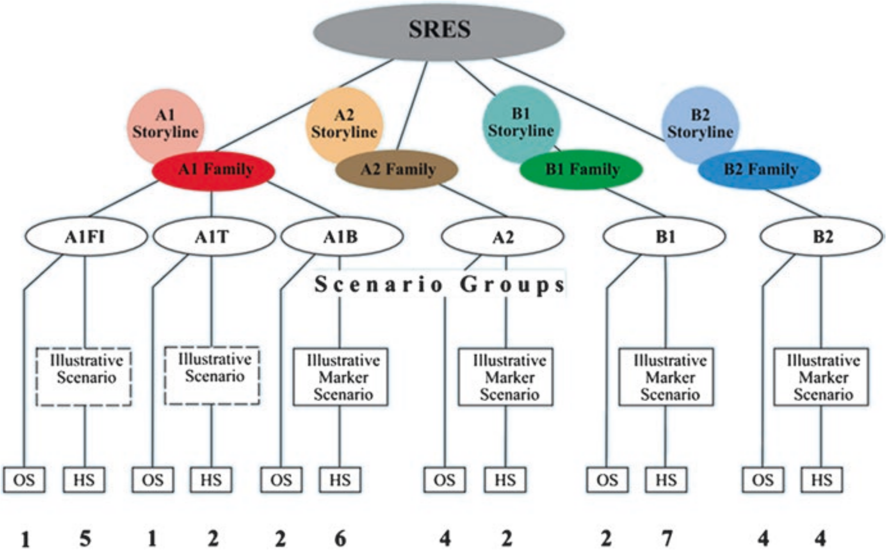


Fig. 22.4 The scheme of SRES (4 SRES storylines are colored and numbers of scenarios are shown at the bottom) (IPCC 2014)

solar cycles, volcanic eruptions, and persistent anthropogenic changes in the composition of the atmosphere or in land use (IPCC 2014).

Since 1992, the Intergovernmental Panel on Climate Change (IPCC) has released emission scenarios to be used for predicting how the future will be like and to which direction and to what extent the driving forces such as demographic, socio-economic, and technological development may influence the carbon emission (IPCC 2014). The ultimate goal is to serve as a guidance for policy-maker to manage in a sustainable way. Currently, 40 scenarios described in Special Report on Emissions Scenarios (SRES) have been commonly used for either mapping the future situation or assessing related impacts of certain mitigation policies and measures. These 40 scenarios, 35 of which are fully quantified, are developed by six modelling teams, basing on four different narrative storylines and associated scenario families (Fig. 22.4).

Climate-Sensitive Active Layer

Active layer is the top layer of the ground undergoing seasonal freezing and thawing and is mostly affected by climate change. The bottom of the active layer usually connects to the permafrost, which is also known as permafrost table or unfrozen soil. The unfrozen soil, also called as talik, may lie between the permafrost table and the bottom of the active layer, the permafrost layer, as well as the space of the blocks of frozen soil.

Some researchers adopt the term of active layer to the ground outside of permafrost, indicating the frequent and profound change of soil and water inside. In this sense, the coverage of active layer can extend to nearly all the area of the mainland USA and Canada (Bockheim and Tarnocai 1998; Lawrence and Slater 2005; Schuur et al. 2008; O'Connor et al. 2010)

22.2.2 Classification and Properties

22.2.2.1 Alpine Vs. Arctic

Considering permafrost's definition of freezing condition, it is understandable that is the permafrost is extensive at the area of low temperature, either high latitude such as Tibet plateau in Asia or high altitude like some mountainous middle-latitude areas, i.e., Rocky Mountains in North America. This frozen ground is known as alpine permafrost.

Subsea permafrost is a relic of the former times which locates around the fringes of the Arctic Ocean. It was formed about 20,000 years ago or even earlier when the sea level was 90 m lower because of the glacial ice that locked the water. It can be found along the fringes of the Arctic Ocean.

However, the permafrost is not the patent for the polar or arctic area, we can still find Eurasian permafrost extending southward to 30th parallel.

22.2.2.2 Continuous Vs. Discontinuous

We also divide the permafrost as continuous and discontinuous permafrost zones, with regard to its different extension, distribution of three layers, and the temperature of the environment (Davis 2001).

The Extension

The discontinuous permafrost refers to the ground of which 30–80% is covered with permafrost, while the continuous permafrost refers to the ground where more than 80% of the surface is underlain by permafrost.

Distribution of the Three Layers

The discontinuous permafrost usually have a relative thick surface layer (active layer) of 1–10 m and a permafrost layers around 30–50 m, while the continuous permafrost may have a few centimeters thin surface zone of annual freeze and thaw, but a thicker permanently frozen layer ranging from 400 m to at most 1450 m.

Temperature

The southern fringe of continuous permafrost has a mean annual air temperature close to −8 °C while the southern limit of discontinuous permafrost corresponds closely to an isotherm of −1 °C.

22.2.2.3 Cryoturbation and Landforms

Cryoturbation occurs in areas of seasonal frost and, more commonly, in permafrost areas (Bockheim and Tarnocai 1998). One of the main formations in the process of cryoturbation leading to the different landforms is Pipkrake. Pipkrakes are

Fig. 22.5 Pipkrakes (Carter, n.d.)

formations of needle ice when the water migrates from bottom soil to surface and freezes, lifting some portions of the ground surface thus creating a karst-like topography. These elongated crystals of ice grow right under the ground surface. The repetitive warming in daytime and freezing in cold nights will create multiple layers of pipkrakes. It can be as long as 10 cm or even more (Zoltai 1978; Peddle and Franklin 1993; Johansson et al. 2006; Romanovsky et al. 2010; Myers-Smith et al. 2011).

Usually, the pipkrakes, or say, ice crystals grow perpendicular to the ground surface, forming an uneven plane or even a steep slope that may lead to soil erosion or displacement of ground for several to several tens of centimeters. It typically contribute to the process of cryoturbation which is a dominant soil process and describes all soil movements due to frost action (Bockheim and Tarnocai 1998). It is actually a churning of soil that may contribute to movement of ground surface and change of particle size and distribution of soil (Bockheim and Tarnocai 1998). Cryoturbation occurs in areas of seasonal frost and, more commonly, in permafrost areas (Bockheim and Tarnocai 1998) where pipkrakes can be formed (Fig. 22.5).

Cryoturbation of subsurface sediments from mechanical freezing processes is able to redistribute these sediments deeper into mineral layers throughout permafrost regions (O'Connor et al. 2010), all thanks to frost action. The frost action is the processes of alternate freezing and thawing of moisture in the soil (Bockheim and Tarnocai 1998). Microscopically, the redistribution from frost action results from water's special properties following the universal system happiness rule.

Theoretically, perfectly pure water can remain liquid when cooled to nearly minus 40 °C. This phenomenon is called super cooling, which can be explained by the universal system happiness rule: *The stable, equilibrium state of a system is the state of minimum free energy*.

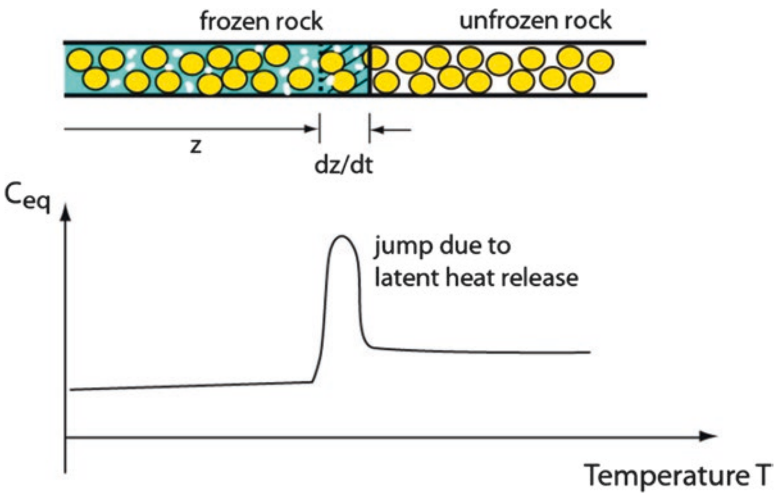


Fig. 22.6 Latent heat release from water to ice (*C*eq means an equivalent heat capacity)

In this statement, the "system" means a group of substances in the equilibrium when it is free of outside influences, e.g., a pail with frozen moist soil. While the "free energy" is the available energy which can drive the system to work, depending on the mass of the system, temperature, location, as well as heat capacity, e.g., sunlight.

In the case of permafrost, when water cools, its decreasing thermal motion allows an increasing number of the water molecules to cling together by hydrogen bonding, leading to a less free energy than unattached molecules. When water cools enough to freeze, the molecules lock together to form fixed pattern of crystal arrays by hydrogen bonds, namely, the ice. Then the energy of water latent heat of fusion will be cast off, decreasing the free energy of the whole system. However, observations show that some unfrozen remains in the soil down to quite low temperatures, coming to the case of super cooling. In this situation, when the water remains unfrozen below 0 °C, this system will be unstable, with the free energy larger than the ice, tending to freeze. In the ice-water mix, a discontinuous heat flux will be expected at the interface between solid and liquid. As Fig. 22.6 (Wan and Booshehrian 2015) shows, the pulse of the latent heat during phase change can serve as either a barrier from water to ice if the energy is not large enough, or an abrupt change to ice if the energy flow has passed the energy wall. A typical figure describing the unfrozen soil water content versus temperature is called soil freezing characteristic curves.

Fig. 22.7 Photo of ground collapse in the Noatak National Preserve in Alaska shows the thawing of permafrost as the climate getting warmer (Resource from Edward Schuur, University of Florida)

22.2.3 Factors of Permafrost Formation

22.2.3.1 Climate and Hydrologic Factors

The twentieth century is an era of climate change, when, by and large, the degradation of permafrost expands at a global scale. Permafrost is now still developing under thickening moss of boreal forests and in the ground on the north side of new buildings for it shadows the midday sunlight. Figure 22.7 provided by the University of Florida shows the Noatak National Preserve in Alaska with erosion and ground degradation because permafrost is thawing more from global warming. Similarly, climate change leads to warmer oceans and more atmospheric water vapor, which can increase overall precipitation, including snowfall (IPCC 2014). Increased amounts of snow can insulate permafrost, leading to warmer winter temperatures and thus deeper thawing (Schuur et al. 2008). Snow coverage can also influence albedo, and whether this is in a positive or negative direction can only be determined in a regional context, considering existing environmental conditions.

The connection between hydrology and permafrost can be explained mostly by the permeability of the ground. Frozen ground is much less pervious to water than unfrozen one, acting as a supporting pan of the above water. This supporting effect will lead to a wet environment in the frozen area.

22.2.3.2 Geographic Factors

The nature of soil, especially the size of the soil particles, is one of the most important factors affecting the permafrost. To be specific, the particle shape and size distribution will affect surface area, which profoundly influences the soil's ability of water adsorption. As we know from the geometrical knowledge, spherical particles have the lowest specific surface while plate-like soil particles have the largest. As a result, sand, which generally shapes as a ball, has specific surface less than 1 m^2/g, while clay may exceed 100 m^2/g for the platy shape (Davis 2001).

Another main property is the cohesiveness of the soil. Crystalline particles like a dry desert sand are very loose and are not attached to each other at all. Some materials may help to cement the particles like humus matter, iron, and aluminum oxides and carbonates. This can be explained in an electrical way. Humus matter, for example, usually carries an excess of negative charge, and therefore attract balancing positive charge layers from air and more typically, water, thus forming a dipolar charge distribution. This electrical attraction along with hydrogen bonding of the water molecules explains why humus matter adsorb water so strongly. This electrical characteristics also lead to the electrostatic attractive forces between the soil particles that help draw the particles together (Davis 2001).

To sum up, various shapes and sized of soil, with different portions of mineral and organic matter, may lead to different strength of soil and interactions with liquids and gases regarding mechanical, chemical, and electrical processes. Soil is a highly complex medium with unexpected stories happening every day, however, if only one factor can be discussed here, the overall characters of soil can all be attributed to climate.

22.2.3.3 Anthropogenic Factors

Although it has been proved that permafrost requires a long period to form, longer than the human history, anthropogenic factors may also be a core contributor to the modification of permafrost.

The direct effects include infrastructure constructions, water withdraw, gas extractions, and transportation. Human activities mostly will affect the active layer, which is highly related to biological diversity and climate change. Studies (Chen et al. 2013) have shown that the anthropogenic influences on the permafrost in Tibet Plateau were significant. It is proved by the remarkable surface settlement along the embankment of Qinghai-Tibet Railway. It is of great importance and necessity to monitor permafrost not only for the highly noticed climate change and fragile ecosystem but also for the regional sustainable development.

Commencing in the late nineteenth century, this frozen ground became a barrier of making money for the gold miners who came to Alaska and northern Canada for the golf buried in the permafrost. They tried to thaw permafrost on purpose for the excavation, leading to a high net cost that could hardly be balanced with profit from mining. Apart from the thawing of the gold-bearing gravels, they also had to thaw down through several tens of meters of silty soil covering above. There are few technique of thawing that have developed since then. One primitive way is to burn wood in a pit. Another advanced way is to throw heated boulders down to the shafts. Fig. 22.8a shows the shaft structure in Fairbanks mining district of Alaska. To accomplish this, so many trees had been cut down, that the miners literally destroyed the nearby forests. Figure 22.8b shows a prospecting boiler rigged to burn fuel oil

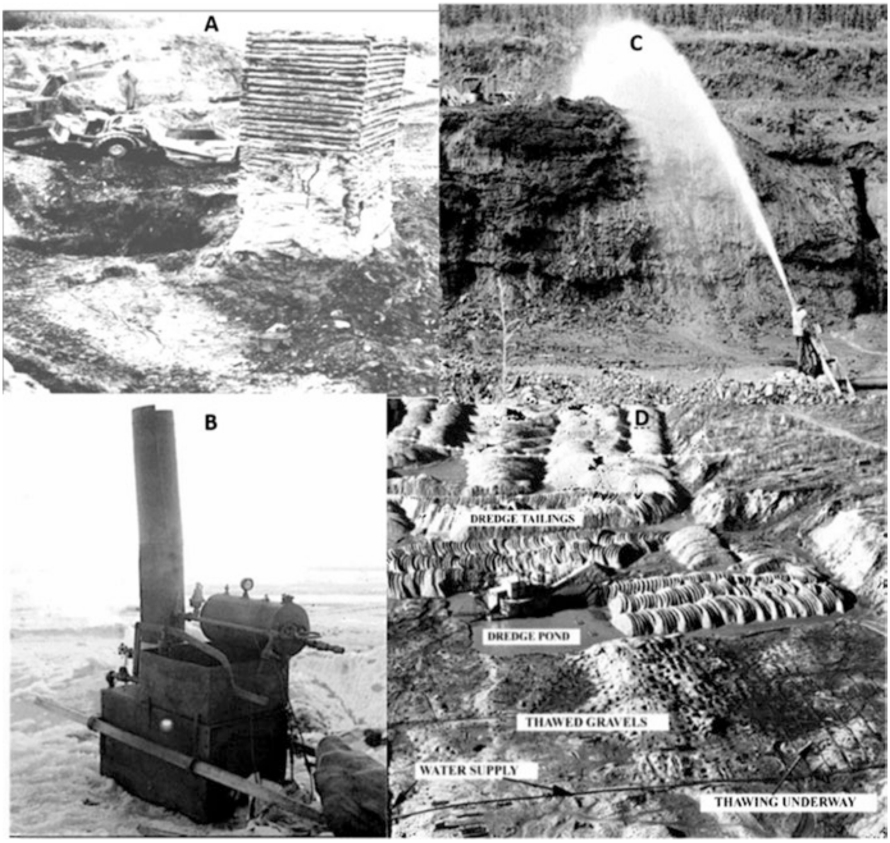


Fig. 22.8 Techniques used for thawing permafrost in Alaska. Resources from Davis (2001)

while Fig. 22.8c used cold water as the main thawing agent. In early 1920s, the large-scale dredging operations commenced within which 12,000–15,000 of thawing points were operated simultaneously. High cost of previous methods kept human searching for better methods of thawing even till now, when permafrost itself starts to speed thawing.

22.2.3.4 Indicators of Change and Measurements

As previously stated, projections under climate change show dramatic permafrost degradation by 2100 (Lawrence and Slater 2005). There are currently around 2 million km^2 of permafrost in the northern hemisphere, and it is predicted that almost all near surface permafrost will disappear by the end of the century, with only 1.0 million km^2 of the total permafrost remaining (Grosse et al. 2011; Lawrence et al. 2008; Lawrence and Slater 2005). It is difficult to accurately quantify the impacts of thawing permafrost because of the difficulty of modelling ice, and the dynamic changes

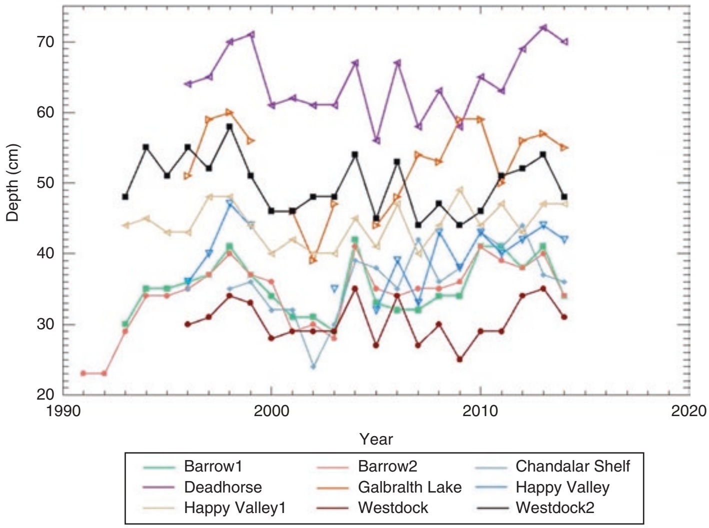
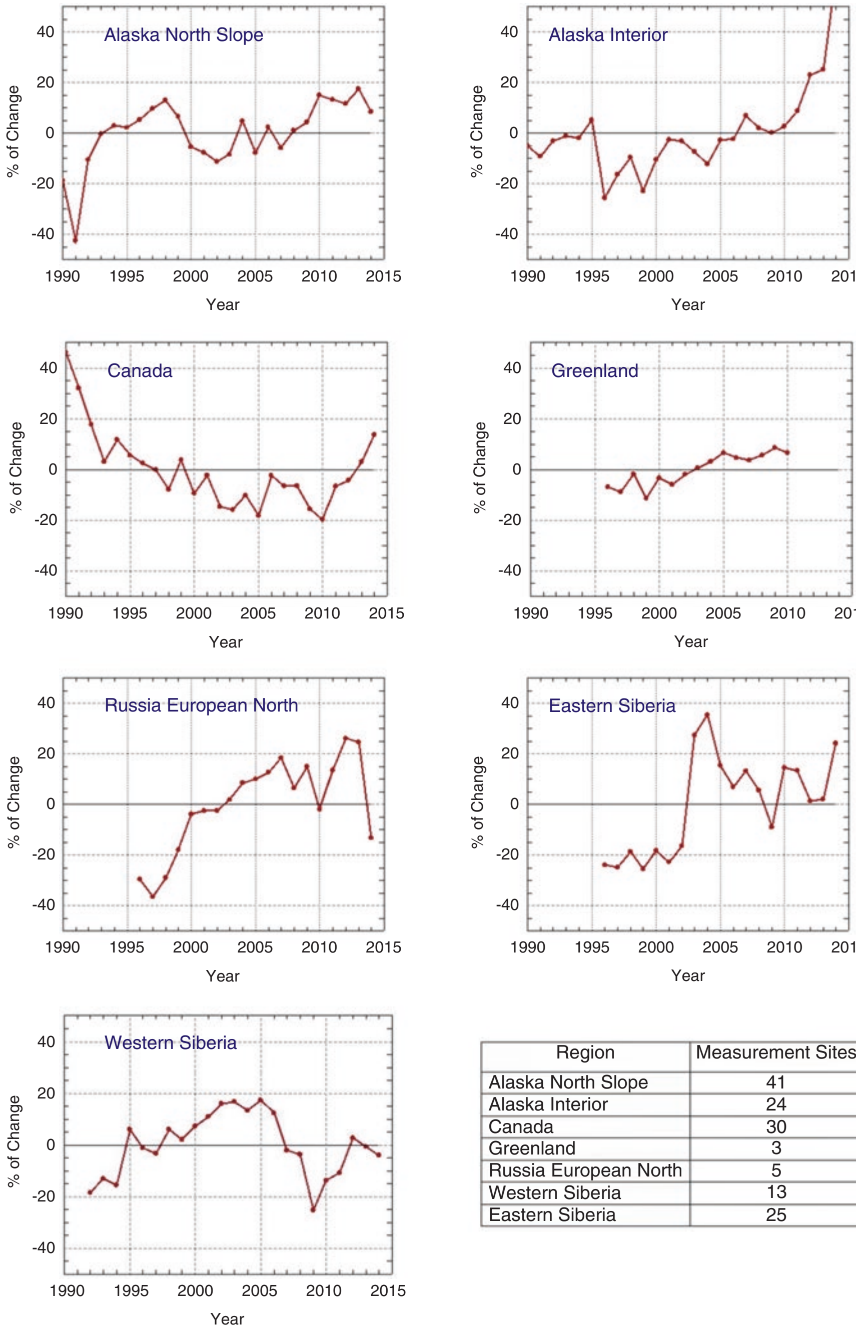


Fig. 22.9 Time series of Active Layer Depth in Alaska Region (Letterly 2015)

in surface properties, vegetation, active layer thickness, water, soils, and ecosystem interactions (Schuur et al. 2008; Grosse et al. 2011). In addition, high uncertainties remain with respect to soil spatial distribution and depth, organic carbon content, and organic matter (Grosse et al. 2011). However, permafrost degradation is expected to have significant adverse ecological and societal effects as it will cause drastic changes to the hydrological cycle, vegetation composition, ecosystem functioning, and carbon dioxide and methane fluxes (Lawrence and Slater 2005).

An important indicator of the change of permafrost is the active layer thickness (ALT). It is a thaw depth which measures the depth of the top layer of soil or rock that thaws and freezes according to the alterations of the seasons (Ye et al. 2003; Chen et al. 2013). It is a sensitive indicator of the surface temperature, showing a changing state of the permafrost. This value can range from several meters to more than 20 m. Prof. Aaron Letterly from University of Wisconsin measured the continuous year-round ground temperature of Alaskan region. The results have shown a record-breaking ALT during 2013, when the active layer of one region named dead horse is as thick as 72 m (Fig. 22.9).

It has also been found a decadal trend of warming in the Arctic region. In Fig. 22.10, seven different Arctic regions have all shown the greater ALTs in recent years than 1991–2014 average (above the solid lines) except for Western Siberia. Shiklomanov et al. (2012) have indicated the contribution of soil types, snow depth, and atmospheric behavior to the variance of ALT.



Region	Measurement Sites
Alaska North Slope	41
Alaska Interior	24
Canada	30
Greenland	3
Russia European North	5
Western Siberia	13
Eastern Siberia	25

Fig. 22.10 Time series of Active Layer Thickness for seven different Arctic regions from 1991 to 2014 (Letterly 2015)

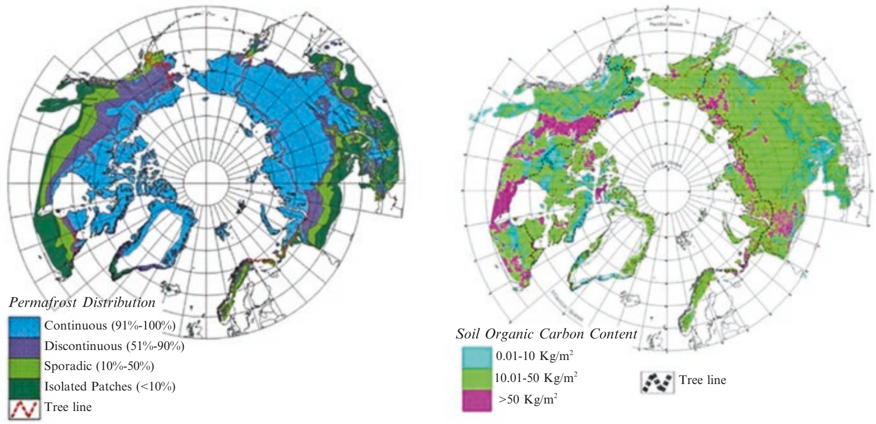


Fig. 22.11 Permafrost distribution and SOC content in the northern hemisphere (Tarnocai et al. 2009)

22.3 Resource Vs. Threat

22.3.1 Extent and Distribution

The total area of soils in the northern circumpolar permafrost region is $18{,}782 \times 10^3$ km^2 (Tarnocai et al. 2009). Approximately 65% of the area occurring in Eurasia and 35% in North America and Greenland (Tarnocai et al. 2009). As seen in the figures below, the largest portion of this soil area, 54%, lies within the Continuous Permafrost Zone (Tarnocai et al. 2009). The remaining 46% is split approximately equally between the Discontinuous, Sporadic, and Isolated Patches permafrost zones (Tarnocai et al. 2009). Permafrost, even though it may not be commonly acknowledged by people, actually covers one-fifth of the earth's land, even drifting on the shallow continental shelves of cold polar seas as subsea permafrost.

Continuous permafrost covers from the pole outward to the surrounding northern parts of Alaska, Canada, and Greenland, most portions in Siberia and the northeast of China. The discontinuous permafrost encompassing the fringes of the continuous permafrost is covering approximately all the area of Alaska, most of Canada and Rocky Mountains in the west of the USA, Greenland, center of Iceland, north of Scandinavia and Europe, and Siberia, and China, especially the Tibet area. Figure 22.11 shows the Northern circumpolar permafrost map and distribution of soil organic carbon contents in the northern circumpolar permafrost region based on the NCSCD.

According to the IPCC's projection, the ice extent may shrink greatly and the boreal forest as well as grassland may in turn extend broadly by the next century as shown in Fig. 22.12. Left is the vegetation map with current Arctic condition basing on floristic survey. Right is the projection of vegetation for 2080-2010 with the Dynamic Vegetation Model under the HadCM2 climate model (scenario). It has

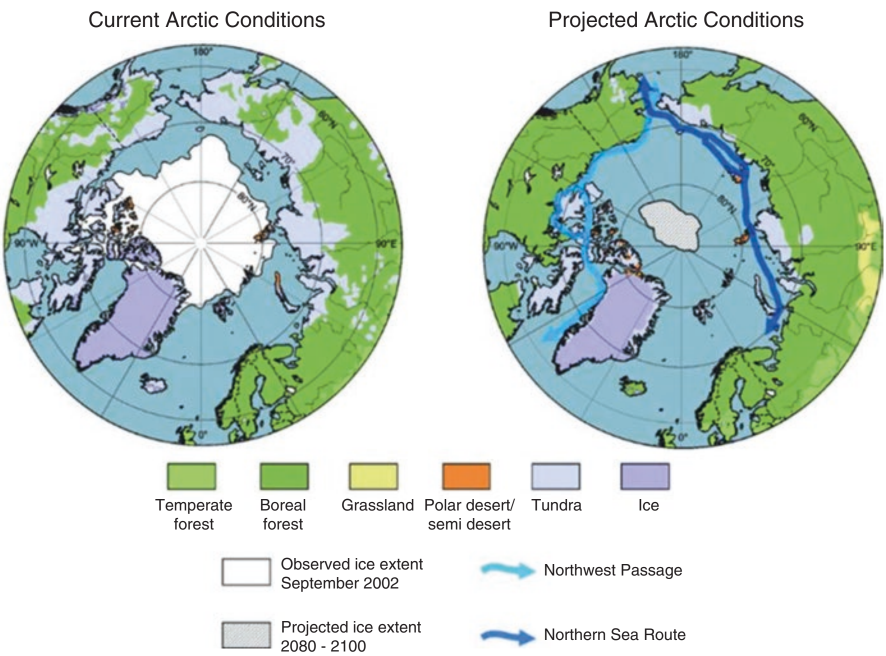


Fig. 22.12 Present and projected condition of sea ice extent and vegetation coverage (IPCC 2014)

shown a general forest expansion to north and the shrinking of ice, leading to the sea level rise, as well as the shrinking of pemafrost. Other threats like the lost for habitats and the flooding of northern coastal wetland will then follow. These projections have indicated the limited capacity for current Arctic ecosystems to adapt to warming. Human, therefore, has to take actions to accomodate or try to be adaptive to the change. Seeing permafrost as a resource or threat will affect human reactions to these changes, which we will discuss in the following sections (IPCC 2014).

22.3.2 Permafrost as a Global Resource

In the past hunter-gather societies in cold lands, Eskimos and other northern residents learned to live in harmony with permafrost. They just obtain food from the sea (like whaling) or nomadic hunting instead of tilling the land or mining for the ores. Permafrost can be a good resource for storing food with little trouble affecting the human life. In winter, people built homes from whale bones, driftwood, and sod which were dug into the ground. In summer, they set up camps on the driest places. Apart from being natural refrigerator, permafrost also became the safe place to bury dead where the desiccating process mummified the frozen bodies, recording the past life sign for current archeological studies.

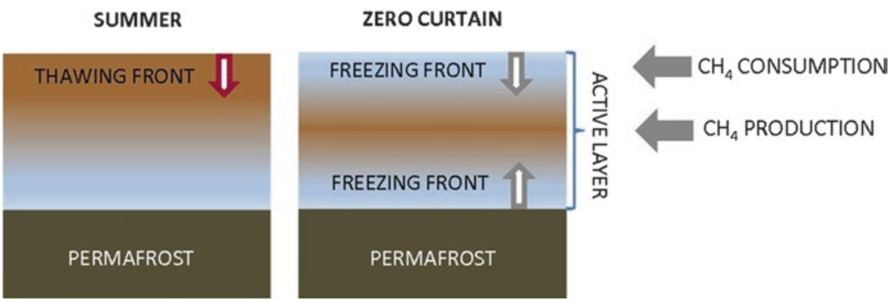


Fig. 22.13 The hypothesized soil physical processes influencing CH_4 production and oxidation depending on the time of the season

Some permafrost can be dated from Pleistocene, when the mammoth and mummified bison existed (Willerslev et al. 2003). Permafrost, in this case, works as an intact record for the ancient cold-climate plant, animal, and human life, helping the archaeologists and paleo zoologists to find the fossil as well as learning the natural way for preservation (Poinar et al. 2006; Heintz and Garutt 1965). It is a fact that by measuring the temperatures in hold drilled into thick permafrost, one can get an insight on the air temperatures during past millennia. So, the permafrost can also be an indicator of climate for the Pleistoscene (Schirrmeister et al. 2002).

Professor Vaks et al. (2013) from the University of Oxford with his colleagues sampled speleothems from six caves around Siberia area and uncovered the historical condition in Siberia about 500,000 years ago. By tracing back, we can recall and even roughly predict the boundary of the temperature limit of the abrupt carbon release. Just 1.5 °C higher than present, continuous permafrost seems to degrade then, leaving no records for the formations in the Ledyanaya Lenskaya Cave any more. Researchers worried that it might be a threshold of temperature for the uncontrolled situation when continuous permafrost zone begin to contribute to global warming with an inevitable speed.

Considering the estimate of 1700 gigatons of carbon stored in permafrost, if all the permafrost start to thaw, it may dwarf the greenhouse gases that human are emitting into the air, roughly twice as much carbon as is currently trapping heat in the atmosphere. However, permafrost can also be a great source of methane. When lacking oxygen, the microorganisms underground will exert anaerobic reaction so as to produce CH_4 instead of carbon dioxide (Zona et al. 2016). Currently in some northern part where permafrost lies, you may find it easy to fire indicating the leaking of the gas. How to manage the energy resource underground remain to be fully studied (Tarnocai et al. 2009; Schuur et al. 2013). Fig. 22.13 (Zona et al. 2016) shows the hypothesized soil physical processes influencing the methane production and oxidation. It is expected that during the zero curtain, the frozen near surface soil layer decreases CH4 oxidation, resulting in substantial CH_4 emissions, even with lower CH_4 production. Light blue represents cooler soil temperatures, and light brown represents warmer soil temperatures; the arrows point in the direction of the thawing fronts in the summer and freezing front during the cold period.

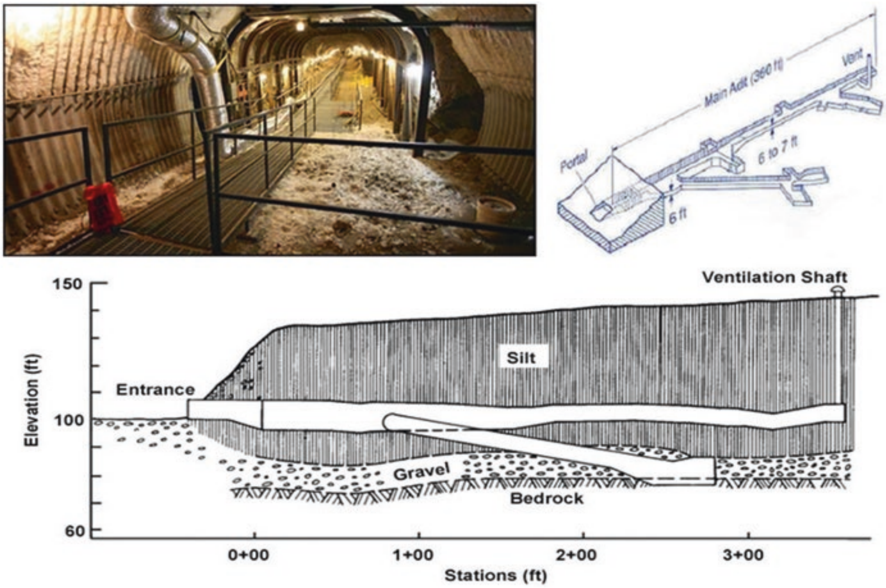


Fig. 22.14 Entrance, structure design, and geological cross section of the Permafrost Tunnel (Resource from CRREL website)

As a good example of setting permafrost as a resource, a Permafrost Tunnel was excavated into a man-made escarpment during the winter months of 1963–1965 by engineers and scientists from CRREL (US Army Corps of Engineers Cold Regions Research and Engineering Laboratory). The tunnel initially served as a research study to test new mining technologies and construction methods in frozen soils. It is approximately 110 m in length, 2–2.5 m high, 4–5 m wide, and 15 m below the surface. The tunnel is composed of two portions: the adit (horizontal passage), which passes entirely through frozen silts, and the winze (inclined adit), which extends off of one side down 45 m passing through silts, a gravel layer, and then into bedrock. The bottom of the winze is approximately 5 m lower than the adit. Figure 22.14 shows the entrance of the tunnel, its conceptual design, and the geological profile.

The CRREL also provided online interactive photograph enabling visitors to have online tour into the tunnel. Figure 22.15 shows one glimpse of the permafrost in the winze. This picture shows the altering of ice-wedge development. The foliated wedge ice has been eroded and replaced by much whiter ice. This white ice is probably the result of the freezing of near surface melt water running alongside the wedge during a warm period. A subsequent colder period captured the subterranean melting event and is now locked in the permafrost.

Fig. 22.15 CRREL Permafrost Tunnel 25 m into winze

22.3.3 Permafrost as a Threat to the Environment

Although permafrost is a good record for history, a good fridge for food, and a great carbon sink, however, this frozen ground was more treated as a threat in most area, especially in the current warming environment (Zollinger et al. 2015).

As we mentioned in 22.2.3.3, when the permafrost froze, it became a barrier of making money for the gold miners who comes to Alaska and northern Canada. They tried to thaw permafrost on purpose for the excavation, leading to a high net cost that could hardly be balanced with profit from mining.

Also, in terms of the hydrology, this solid boundary is highly impermeable to water supply and wastewater disposal. They also impede the conventional piping. People living on permafrost sometimes have difficulty in getting the water. Even though there may be viable water in the thaw bulbs of rivers and lakes in the continuous permafrost or non-frozen soils in the discontinuous permafrost. Water quality is usually unsatisfying, either saline, iron-rich, or have high hardness (Woo 1986).

Permafrost will not only impede the flow of water but also become a barrier for roots. Boreal grown in the area with shallow permafrost table will have a shallow thus fragile root system. However, on the other hand, the haunted water may lead to a surprising existence of vegetation in the high altitude area. The US Bureau of Land Management (BLM 1986) once had a headache with the permafrost, because the permafrost allows moss, sedges, bushes, and trees, usually found in the lowland areas, to grow on hillside, where they were building road in the north of Fairbanks, Alaska. The unexpected growth of boreal on the upland areas led to higher cost for the permit to disturb land designated as wetlands (Slaughter et al. 1990).

Fig. 22.16 Collapse of the building due to permafrost thawing, photo by V.E. Romanovskiy

With regard to the cases above, it seems we are suffering from the frozen ground and hoping it to thaw. However, when permafrost really thaws, it may also lead to other problems. In the great northern expanse of Russia, where buildings were often erected on frozen ground but are now collapsing due to the thawing of the ground (Anisimov and Reneva 2006). People in the northern area had problems in building roads on permafrost. It is a hazardous geological threat considering that it encompasses deposits of pure or nearly pure ice. When the temperature is cold enough, the ice formed in the permafrost can be a strong support for heavy loads, while these constructions relying on permafrost may become disasters or at least lead to a mess when temperature rises, and ice begins to melt. Those once strong structures will become soft and fragile, even void as the melting water flows away. Man-made structures including roads, pipelines, residential and public buildings, and utility systems will all be affected dramatically. It may create a great economic loss no less than the earthquake or hurricane. People have to build the pipeline above ground to help preserve the permafrost underneath (Davis 2001). Residents who built homes over permafrost will see them distorted and destroyed as the temperature increases and permafrost below melted (Fig. 22.16). The Alaska Highway, firstly constructed in World War II, has to be rebuilt because of the thawing permafrost underneath, forming a quagmire.

This collapse usually results from frost heave. It is a process relating to the aforementioned segregation ice. As the super cooling water spread into the ice-holding layer and increase the volume of the total ice, the soil will swell to have higher elevation than the surrounding land. In places with fine-grained soils and plenty of water, frost heave may exert powerful forces that lift entities such as telephone poles, pilings, and even buildings up out of the ground. The government agencies in the north simply adopt the constructing techniques obtained from normal warm areas to the permafrost, regretfully seeing them collapse or deformed due to the thawing of permafrost. The frost heave will alter soil particles and redistribute the soil size fractions forming distinctive topography (Davis 2001).

Also, on sloped surfaces, needle ice may be a factor contributing to soil creep. The needle ice, or say, pipkrakes formed by the up flowing and freezing water in soil may be found in the loose soil and they also have the tendency to loosen the soil. This positive cycle may gradually generate great impacts on soil. In high wind area, the frozen layer of pipkrakes below the surface will lift up the fine-grained top soil and lead to the wind removal of small grains like clay, silt, and sand. It is a serious problem in terms of agriculture, so the farmers sometimes will try to compact pipkrake-prone soil to reduce the tendency of forming pipkrakes.

It is also a great challenge to set up transportation facilities on either seasonally or perennially frozen ground. Engineers have found reasonable ways to tackle the problem for pipeline while the construction of safe roads and railways remain to be explored. One of the amazing projects building on the permafrost is the Qinghai–Tibet Engineering Corridor (QTEC) from Golmud, Qinghai Province in the north, to Lhasa, Tibet Autonomous Regions in the south, encompassing a naturally occurring north-south corridor in the central area of the Qinghai–Tibet Plateau (QTP). About 80% of this corridor exceeds 4000 m in elevation while a portion of it, about 50 km, exceeds 5000 m. As you can see in Fig. 22.17, the QTEC crosses three major mountain ranges: the Kunlun Shan, Fenghuo Shan, and Tanggula Shan and is subject to below-zero ground temperature. These high elevations, periglacial processes, and cold and arid continental climates lead to the vulnerable permafrost environments along the QTEC. The total length of the QTEC from Golmud to Lhasa is about 1120 km; of which permafrost impacts about 531 km. The total length of the QTEC is subject to seasonally frozen ground, including frost heave in winter and differential thaw settlement in spring.

22.4 Discussion

22.4.1 Ecosystem Vs. Permafrost

Cryosphere is a useful indicator of the climate change, considering its melting sensitiveness to climate change. This sphere includes sea ice, river and lake ice, snow cover, glaciers, ice cores and the last but not the least, permafrost. The size, extent, and position of margins of these elements will finally give us valuable information about the global climate change and its corresponding results throughout the whole ecosystem (IPCC 2014).

The pedosphere, which is also inclusive of permafrost, actively interacts with all four other spheres: the biosphere, lithosphere, atmosphere, and hydrosphere. However, permafrost regions, and interactions regarding permafrost carbon, are poorly understood. The research on the carbon-related effects of permafrost, though in its infancy, has demonstrated the importance to understand current interactions between permafrost and different spheres so as to provide a baseline for the accelerated changing environment.

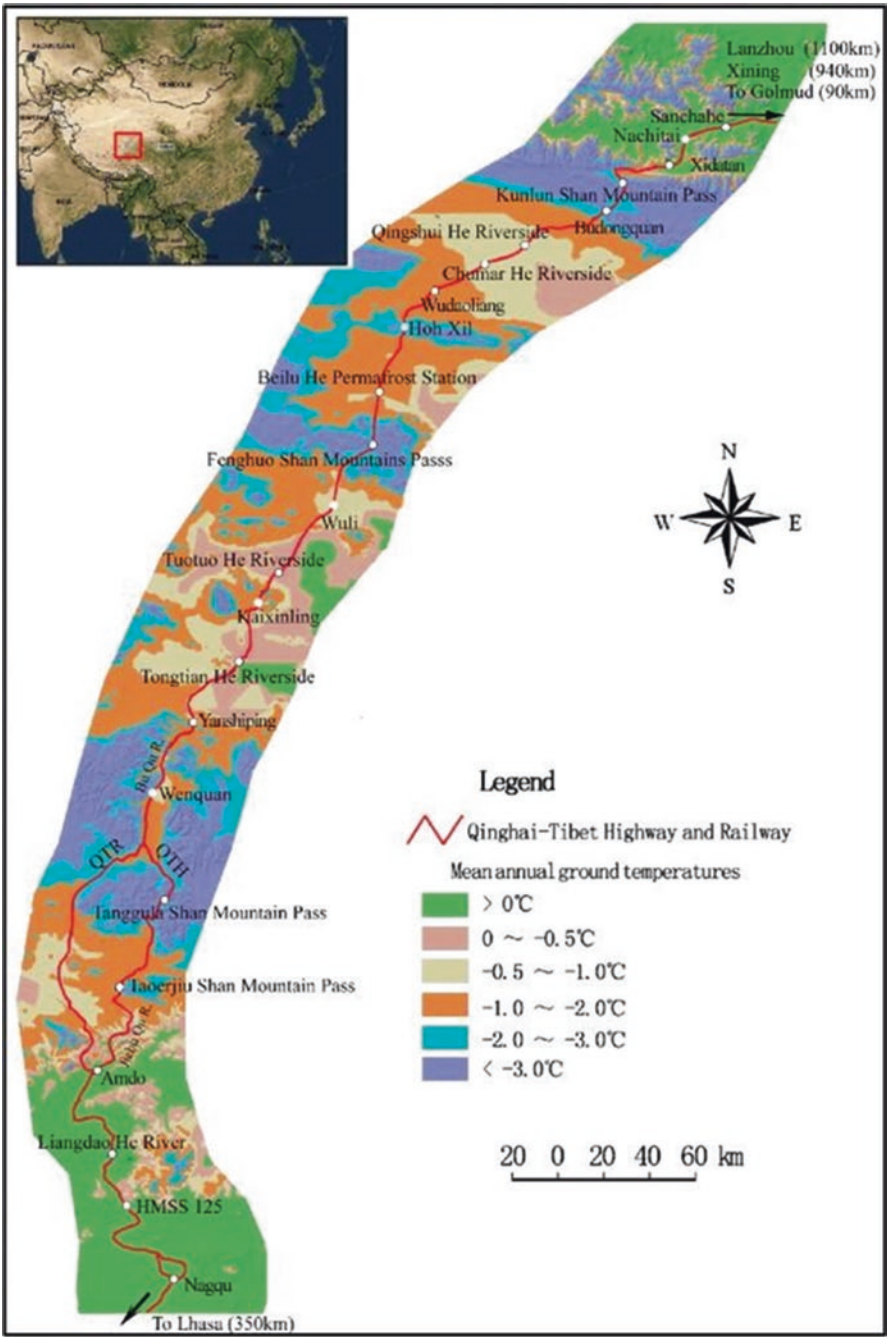


Fig. 22.17 Qing-Tibet engineering corridor (Jin et al. 2008)

22.4.1.1 Atmosphere

The pedosphere, which includes permafrost, is in a constant interaction with the atmosphere. It is mainly through microbial anaerobic and aerobic processes that gases are exchanged from one sphere to another (Rivkina et al. 2004). Another method of exchange between the atmosphere and permafrost soils is through the cryoturbation of wind borne sediment that is deposited over the course of hundreds and thousands of years (Schuur et al. 2013).

Of the greenhouse gases in the atmosphere, CO_2 is the most important and potentially devastating greenhouse gas in regard to climate change. CO_2 is released from the soil into the atmosphere by aerobic respiration conducted on organic carbon in the soil. The pedosphere is also accountable for roughly a third of CH_4 emissions and two-thirds of N_2O emissions to the atmosphere (Smith et al. 2003). These greenhouse gases have 23 times and 300 times the infrared absorption potential of CO_2, respectively, and therefore possess the capacity to vastly impact the future climate (Smith et al. 2003). It should be noted that since many research studies have reported exponential increases in N_2O emission rate with increasing temperature, and since permafrost is sub-zero, the focus in regard to greenhouse gases and permafrost is generally focused on the exchange of CH_4 and CO_2 (Smith et al. 2003). Currently high-latitude soils, including permafrost, are a sink of atmospheric CO_2 but a source of atmospheric CH_4 (O'Connor et al. 2010).

22.4.1.2 Biosphere

Permafrost as one kind of soil that contains a complicated environment including organic matter and metal, though is frozen and underground, is not lacking in living organisms. Permafrost, being perennially frozen, represents a unique opportunity as a stable, non-extreme, physical-chemical environment that has allowed prolonged survival of ancient microbial lineages (Rivkina et al. 2004). Permafrost contains as many as 108 cells/g of viable microorganisms including aerobes, anaerobes, cyanobacteria, green algae, yeast, and fungi, many of which are in frozen states (Rivkina et al. 2004). Although many of the microorganisms are frozen, some do still have the capacity to perform their metabolic processes in the sub-zero temperatures, effectively circulating organic carbon and nutrients in the soil, allowing for uptake from vegetation roots (Rivkina et al. 2004). Permafrost provides the only community for microorganisms that is known to retain their viability over geological time (Rivkina et al. 2004). Therefore, upon thawing, the frozen microorganisms can renew their physiological processes (Rivkina et al. 2004). This means that should the permafrost thaw due to anthropogenic or natural causes ancient life will be exposed to modern ecosystems (Rivkina et al. 2004).

22.4.1.3 Hydrosphere

The current understanding of hydrological cycles and processes in cold regions remains inadequate (Woo 2008). Most of the current interest in high-latitude hydrology has been fueled by concerns about climate change (Woo 2008). Few hydrological processes of permafrost are considered to be certain, but one of these processes that has been studied and confirmed is the freeze-thaw mixing of water sediment depositions that has buried carbon many meters deep in permafrost soils (Schuur et al. 2013). Though with the current rates of permafrost warming, the size and length of active layer thawing is increasing, allowing water to flow through more freely, which will in turn change the freeze-thaw mixing of sediments (Woo 2008).

Permafrost also influences hydrology by providing an impermeable barrier to the movement of liquid water (Lawrence and Slater 2005). The permeability/non-permeability of permafrost is thought to possibly have an effect on streamflows in cold regions. An example of the Eurasian river runoff studies suggested increasing runoff between the years of 1950 and 1988, which correlates to the permafrost melting and the active layer being thawed for longer (Woo 2008). Though multiple rivers have shown increased runoff, it is not entirely clear how concretely changes in streamflow are related to permafrost melt (Woo 2008).

In addition to the uncertainty about streamflow, the associated hydrologic feedbacks between the atmosphere, ecology, and the physical environment to permafrost remain quantitatively uncertain (Woo 2008). The current research on the subject does show strong indications that large-scale change in surface moisture may alter the surface albedo and evaporative fluxes, which would in turn affect atmospheric energy and water budgets (Woo 2008). Looking forward hydrologic knowledge is of paramount importance to water supply, flood control, and development projects in permafrost regions (Woo 2008). More studies on the effects of permafrost and the hydrosphere will need to be conducted to accurately predict what future changes will occur in the event of permafrost thaw.

22.4.1.4 Lithosphere

The interactions between permafrost and the lithosphere have been studied less than the interactions between permafrost and the three other spheres. This can most likely be attributed to the fact that the thawing of the permafrost will affect the three other spheres in ways that have more tangible and predictable anthropogenic repercussions.

The most common mixing permafrost undergoes is cryoturbation, which, through freeze-thaw processes mixes materials down from the pedosphere to the lithosphere (Schuur et al. 2008). It is important to note that for cryoturbation to occur all the way down to the lithosphere, the permafrost must be entirely an active layer. Otherwise the stable layer, which is permanently frozen and does not undergo free-thaw changes, will be impermeable to changes (Schuur et al. 2008). With the current climate conditions, ground ice can be up to 80% of the total soil volume, with less ice generally occurring over non-porous bedrock material (Schuur et al. 2008). The thawing of this ice could severely impact topography and ecosystems, although how it will affect the lithosphere is unclear (Schuur et al. 2008).

22.4.1.5 Topography

The thawing of permafrost, which can be up to 80% of the soil volume, can severely impact the topography by changing the physical foundation, and hydrological and nutritional conditions of the soil (Schuur et al. 2008; Christensen et al. 2004). The loss of ground ice can strongly influence carbon dynamics in local ecosystems.

The changing distribution of this ice will also influence the overall surface hydrology, and topography, which will in turn affect the surface vegetation. When ground ice melts and the soil collapses into the space previously occupied by ice volume, a lake can form on the surface, creating what is referred to as a thermokarst terrain (Schuur et al. 2008). Thermokarst often occur in discrete locations on the landscape and can have large consequences for carbon storage and ecosystem carbon cycling (Schuur et al. 2008). They can also trigger positive feedbacks in accelerating subsidence of land, permafrost thaw, and greenhouse gas emissions (Grosse et al. 2011). In addition, climate change will accelerate erosion rates along coastlines, which will affect permafrost thawing, along with increasing seawater temperatures, and a decreasing sea ice (Grosse et al. 2011).

22.4.1.6 Vegetation

One of the most significant and visible impacts of climate change is shifts in vegetation communities and net primary productivity. As previously discussed, northward shifts of shrubs and boreal forests are expected as the globe warms. As temperatures warm and the active layer thickens (freeing up nutrients, as well as a larger area for root development), net primary productivity is expected to increase in the high latitudes, which result in a direct uptake of carbon from the atmosphere (IPCC 2014). Additionally, Christensen et al. (2004) found that studies demonstrated "that the individual vegetation communities are relatively robust in their correspondence with CH_4 emissions when normalized to climatic factors, particularly temperature and moisture." This means that a shift in habitats and hence vegetation composition alone indicates a predictable change in the range of CH4 emissions (Christensen et al. 2004; Lawrence and Slater 2005; Grosse et al. 2011; Myers-Smith et al. 2011).

An example of a negative feedback regarding vegetation composition is the replacement of coniferous trees with more deciduous trees, which will lead to more reflection of radiation off the broad leaves, a higher albedo, and thus decreased warming in the localized area (Schuur et al. 2008). However, if currently ice and snow-covered areas are colonized by vegetation, a decrease in albedo can be expected, leading to increased warmth and thus more permafrost thaw. Lawrence and Slater (2005) estimated that northward expansion of shrubs and boreal forests "may result in a further positive climate feedback if, as anticipated, the negative feedback associated with forest sequestration of carbon is compensated for by a stronger positive feedback related to lower albedos over snow-covered shrubs and forests compared to snow-covered tundra."

The effects of climate change on ecosystem are likely to be more pronounced in higher latitudes, since even the slightest changes in mean annual temperature can cause major disruptions to ecosystem structure (Christensen et al. 2004). The changes that will occur in permafrost can potentially result in major variations of its physical foundation, along with the hydrological and nutritional conditions of the soil (Christensen et al. 2004). These affected systems determine micro-topography of the surface, and ultimately establish the structure and productivity of its vegetation (Christensen et al. 2004).

As permafrost melts, ecosystems tend to get wetter and there is a northward expansion of shrubs and forests (Lawrence and Slater 2005). Wet and semi-wet areas have increased in size on the cost of the dry elevated areas, with permafrost-dependent vegetation types fragmenting (Christensen et al. 2004). The climate change projections show the future climate above the Arctic Circle will closely resemble present-day boreal forests in terms of air temperature and water availability (Lawrence and Slater 2005). This will be caused by the conversion of ice to liquid, which in turn will make water more available to plants and will increase the overall soil water availability (Lawrence and Slater 2005). A change from relatively dry, elevated, shrub-dominated vegetation types to lower, wet grass-dominated vegetation was observed following changes in the underlying permafrost distribution, which determines the surface topography and hydrology, and therefore the plant community structure (Christensen et al. 2004). When normalized to the climatic factors like temperature and moisture, vegetation communities are relatively robust with respect to methane emissions (Christensen et al. 2004). The northward expansion of shrubs and boreal forests indicates a change in the ecosystem carbon balance and methane emissions, and may therefore result in a further positive climate feedback (Lawrence and Slater 2005; Christensen et al. 2004). A shift in habitats and vegetation composition alone has caused a 22–66% increase in methane emissions from 1970 to 2000 through micro topographical and hydrological changes (Lawrence and Slater 2005).

22.4.2 Climate Change Vs. Permafrost

22.4.2.1 Accelerating Carbon Release

With continual human advancement in recent history, anthropogenic emissions of greenhouse gases are increasing, breaking the balance between sources and sinks (O'Connor et al. 2010). Due to the greenhouse effect, increased levels of atmospheric greenhouse gas emissions are causing a corresponding increase in average global temperatures, leading to regionally variable changes in climate. The lowest warming scenario projects 1.5 °C warming in the Arctic by the year 2040, and up to 2 °C warming by 2100, while the highest warming scenario shows a 2.5 °C warming by 2040, and 7.5 °C by 2100 (Schuur and Abbott 2011). This will cause a degradation of the upper 3 m of permafrost varying from 9 to 15% by 2040, increasing to 47 to 61% by 2100, and 67 to 79% by 2300 (Schuur and Abbott 2011). The increasing rates and large amounts of carbon potentially being released into the atmosphere is to cause for serious concern, especially since its impacts are still highly uncertain (Schuur and Abbott 2011). Along with carbon dioxide, atmospheric methane concentrations have also increased dramatically from 715 ppb in the eighteenth century to 1774 ppb in 2005 (O'Connor et al. 2010). The estimated carbon release into the atmosphere from the degradation of permafrost over the next three decades is between 30 and 63 billion tons (Schuur and Abbott 2011). This adds substantially to the grand total of predicted atmospheric carbon levels. These levels are predicted to reach 234–380 billion tons by 2100, and 549–865 billion tons over the next few

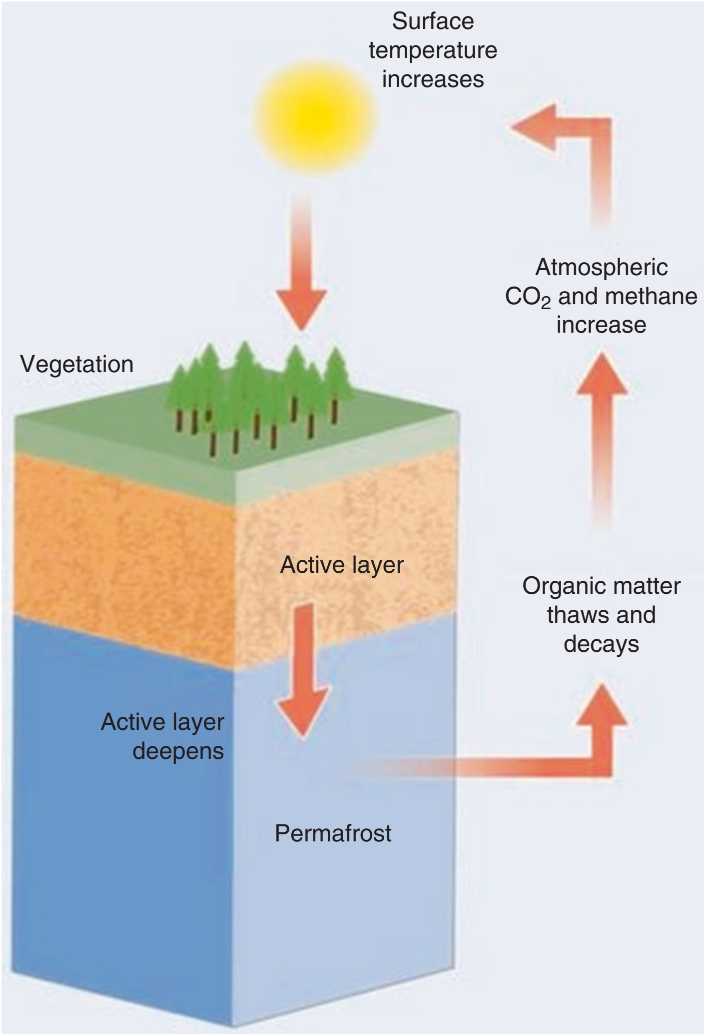


Fig. 22.18 Carbon cycle accelerated by permafrost

centuries (Schuur et al. 2011). Figure 22.18 shows the accelerated carbon cycle fueled by permafrost (Schaefer et al. 2014). Figure 22.19 shows the various time series of carbon dioxide emission obtained from Keeling Curve (https://scripps.ucsd.edu/programs/keelingcurve/).

22.4.2.2 Sea Ice Melting and Improved Drainage

One of the main indicators of climate change is the sea ice extent. Figure 22.20 shows March and September sea ice extent from observations compared with the screened IPCC AR4 models. It is not surprising that the sea ice extent is shrinking

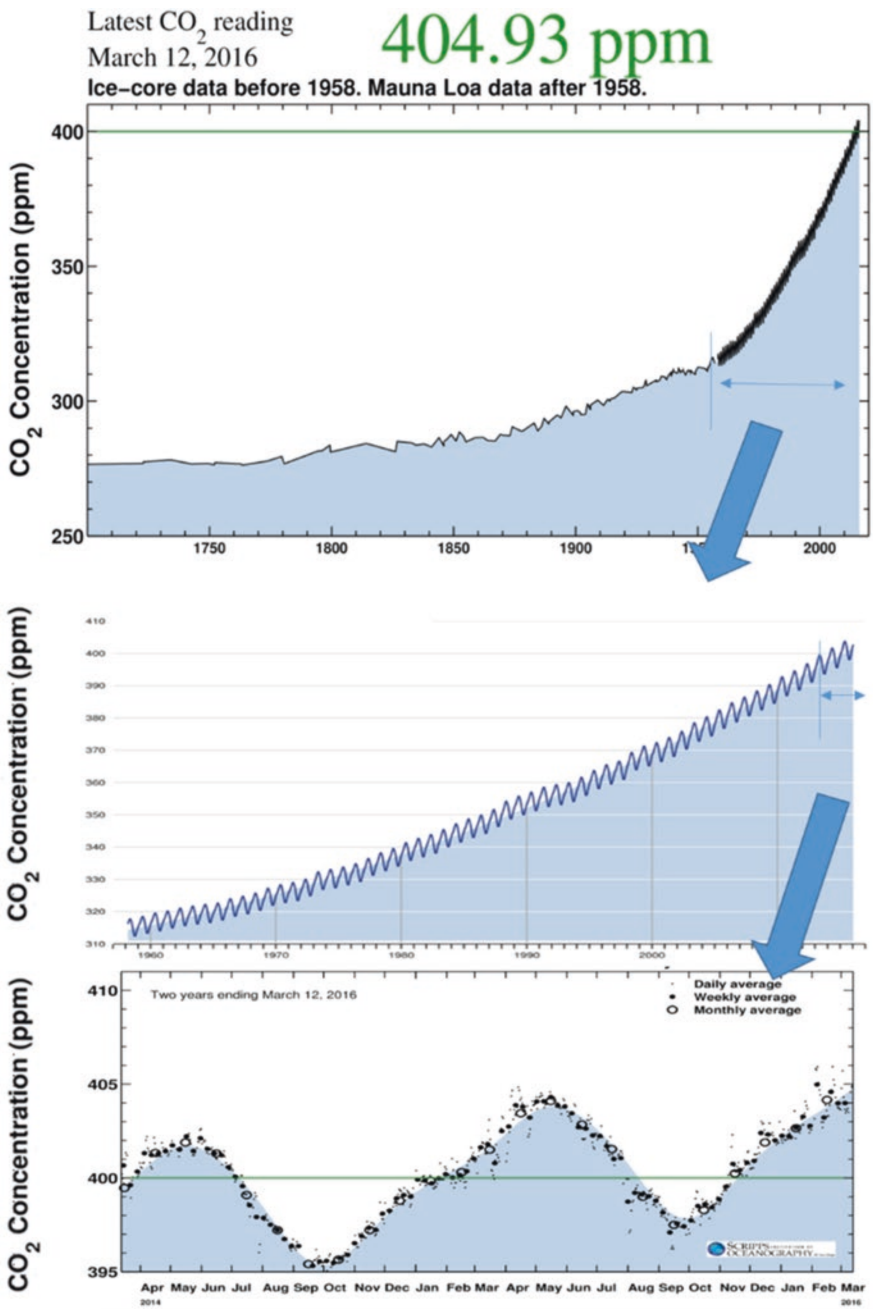


Fig. 22.19 The Keeling Curve showing record of carbon dioxide concentration with different time scale

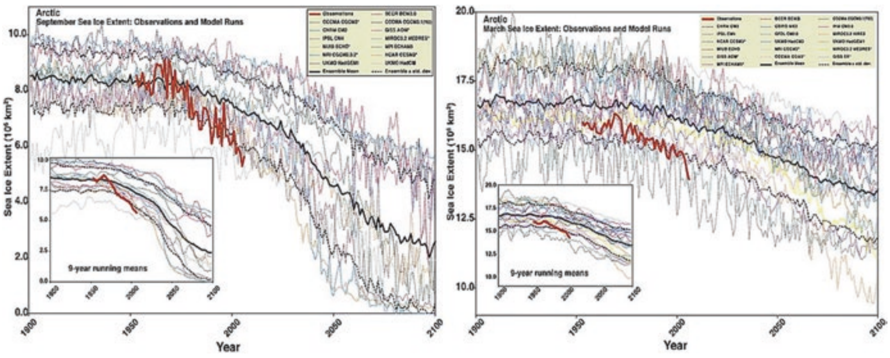


Fig. 22.20 Arctic March and September sea ice extent (×10^6 km^2) from observations (*thick red line*) and 18 IPCC AR4 climate models together with the multi-model ensemble mean (*solid black line*) and standard deviation (*dotted black line*). Models with more than one ensemble member are indicated with an asterisk. Inset shows 9-year running means (Stroeve et al. 2007)

for these half of a century since 1953 for −7.8 ± 0.6%/decade, however, the point that scares scientists is that none of the models we have ever predicted have trends as large as observed for this period. The multi-model mean trend is only −2.5 ± 0.2%/decade, three times less than the real situation. It seems that the current scenario has outweighed our most wild predictions, which probably indicates an uncontrolled situation of climate change we are undergoing. Another closer look at the trend is a series of extremely low September sea ice conditions during the last decade, including the unprecedented declines in 2007 and 2012, suggests a recent acceleration in the long-term Arctic sea ice loss (e.g., Stroeve et al. 2012). This bears resemblance to the so-called Rapid Ice Loss Events simulated in a number of climate models (Holland et al. 2006). These simulated events result when anthropogenic change is reinforced by natural variations. They appear to be triggered by increases in ocean heat transport from the North Atlantic to the Arctic and are amplified by the ice-albedo feedback. In the most dramatic of the simulated events, the September ice pack undergoes a 4 million square km loss (about 60% of the 1979–2000 ice cover) in only a decade, leading to near ice-free September conditions by 2040.

The continuing degradation of permafrost may be one of the contributing factors of this significant decrease, finally influencing the Arctic hydrology. As the soil temperature rises to near 0 °C, soil ice begins to melt, converting frozen soil water to liquid water (Lawrence and Slater 2005). The liquid water will drain through the soil column more readily due to the lack of a soil ice barrier (Lawrence and Slater 2005). Since a larger fraction of water will permeate the soil, runoff is redistributed into subsurface runoff. Surface runoff will decrease and occur at a rate slower than precipitation whereas subsurface runoff increases and will occur at a faster rate than precipitation (Lawrence and Slater 2005). Although precipitation is projected to increase substantially, this enhanced drainage through the soil column results in a slow drying of the soil, decreasing soil water storage. In addition, freshwater

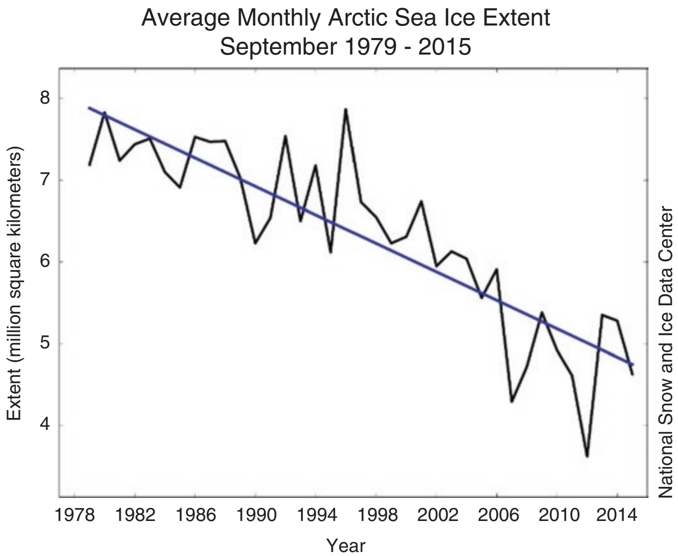


Fig. 22.21 Average monthly arctic sea ice extent from September 1979 to 2015 (Stroeve et al. 2012)

discharge into the Arctic Ocean, which has already been increasing by 7% over the last 70 years, is projected to increase by 28% by 2100, of which 15% is attributed to thawing of permafrost (Lawrence and Slater 2005). Changes in the amount of freshwater added to the Arctic Ocean can have a significant effect on sea ice formation and may also alter the oceanic thermohaline circulation (Lawrence and Slater 2005). Furthermore, the melting of ice in permafrost results in subsidence, or the gradual sinking of land, and water impoundment (Grosse et al. 2011). Thermokarst lakes, or bodies of freshwater formed in a depression by meltwater, are created in this process and trigger positive feedbacks in accelerating subsidence and permafrost thaw, as well as enhancing greenhouse gas emissions (Grosse et al. 2011).

22.4.2.3 Active Microbial Decomposition

Bacteria in the active layer of permafrost produce carbon emissions as they "oxidize organic C to inorganic forms primarily to extract energy for growth from these reduced compounds" (Anisimov 2007; Schuur et al. 2008). However, microbial respiration in permafrost usually occurs at relatively low rates, since although enzymatic reactions can occur below freezing temperatures, diffusion of substrates and enzymes is extremely slow in frozen soil water (Davidson and Janssens 2006). Decomposition rate is dependent on temperature, moisture availability, nutrient availability, and electron acceptor (oxygen) availability (Schuur et al. 2008). Temperature sensitivity of decomposition rates are also affected by physical protection of aggregates, chemical protection, drought, flooding, freezing (Davidson and Janssens 2006).

The large amount of carbon in permafrost could act as a positive feedback to climate change because of the enhanced respiration rates that occur when the major constraint on organic matter decomposition—low temperature—is removed (Koven et al. 2011; Davidson and Janssens 2006). Permafrost thawing (active layer thickening and talik formation) is gradual and exposes organic C to microbial respiration, which is the dominant continuous process affecting decomposition rates. "As soils defrost, microbes decompose the ancient carbon and release methane and carbon dioxide. Not all carbon is equally vulnerable to release: some soil carbon is easily metabolized and transformed to gases, but more complex molecules are more difficult to break down" (Schuur and Abbott 2011). A combination of increased N and organic matter availability and increased temperatures is expected to lead to accelerated rates of microbial decomposition, and the corresponding release of carbon into the atmosphere (Schuur et al. 2008). However, Schuur and Abbott (2011) point out the difficulty in determining the magnitude of carbon emissions that arises from the complexity of these systems.

Most large-scale models simulate future temperature of permafrost soils by assuming that as the air warms, the soils will warm the same amount with a time delay. This warming then increases microbial activity and carbon release. But this is a simplification. Abrupt thaw processes can cause ice wedges to melt and the ground surface to collapse, accelerating the thaw of frozen ground. Evidence for this type of rapid thaw is widespread (Smith et al. 2005; Davidson and Janssens 2006). This indicates the large uncertainty surrounding feedback rates, and suggests that it is particularly important to reduce the probability of abrupt changes as much as possible.

Another factor to consider is the differences in the type of emissions produced in different environments. While mineral soils often experience rapid carbon loss, peat accumulation rates and methane emissions may increase as organic soils thaw (Grosse et al. 2011). As permafrost thaws, Davidson and Janssens (2006) predict landscapes with "a mosaic of flooded thermokarst lakes interspersed within higher dry areas." They suggest that aerobic respiration and decomposition should proceed relatively quickly in dry areas, with large fluxes of carbon dioxide into the atmosphere. In contrast, thermokarst lake systems are likely to be dominated by anaerobic decomposition, which may emit methane at lower rates. However, due to the high radiative forcing value of methane, these emissions may ultimately cause a stronger feedback than the carbon dioxide released from drier areas.

22.5 Conclusions

Permafrost is a complex system of the pedosphere with elaborate interactions between the all four other spheres; the biosphere, lithosphere, atmosphere, and hydrosphere. With continuous climate change, the huge amount of carbon stored in the permafrost is potentially the most significant carbon-climate feedback. How the permafrost interacts with the four spheres and how it will be affected by climate change are not yet fully understood and are cause for great concern.

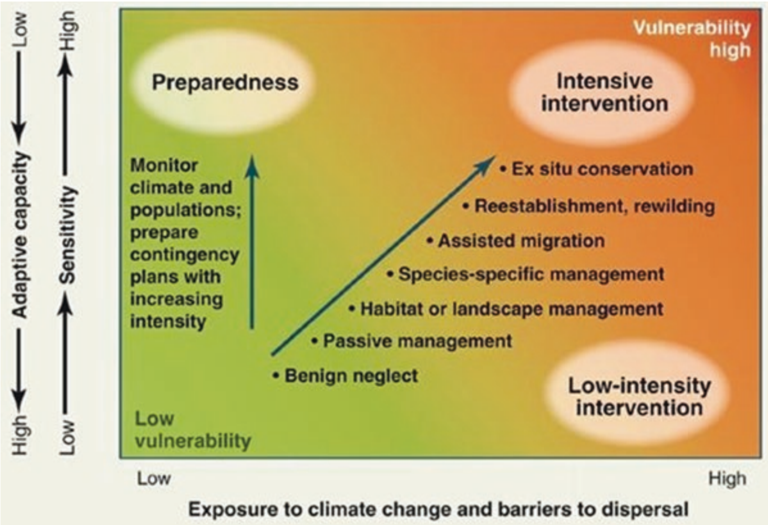


Fig. 22.22 The matrix of vulnerability to climate change and the ability to react from human side (White et al. 2014)

Climate change and the increase of global temperature is causing fast degradation of permafrost, which has profound effects on the environment. The changes in permafrost caused by climate change are expected to have significant adverse ecological and societal effects by causing changes to the active layer, hydrological cycle, vegetation composition, topography, ecosystem functioning, and carbon dioxide and methane fluxes.

Furthermore, permafrost thawing is expected to create a large flux of carbon into the atmosphere. The permafrost carbon feedback (PCF) is the amplification of anthropogenic warming due to carbon emissions from thawing permafrost. If temperatures rise and permafrost thaws, the organic material will also thaw and begin to decay, the increased rates of microbial respiration thus release carbon dioxide (CO2) and methane (CH4) into the atmosphere and amplifying the warming due to anthropogenic greenhouse gas emissions. In this way, a positive feedback from the permafrost regions will have high significance in warming the planet.

Since this subject has significant implications for human and ecological health, further research should be conducted to better understand the system and its complexity. More research will aid in the development of a better understanding of mechanisms and allow us to more accurately predict the actual magnitudes of values. In addition, it would allow us to develop practical ways to minimize and reduce negative impacts of permafrost melting.

This has significant implications for human activities. The IPCC report (2014) states that "adaptation measures [will be] unable to prevent substantial change" in projections for decrease in permafrost, and the following increase in greenhouse gas emissions. Accounting for this, it is crucial that "factors inducing high-latitude climate warming should be mitigated to minimize the risk of a potentially large carbon release that would further increase climate warming" (Zimov et al. 2006).

As shown in Fig. 22.22, improved understanding of adaptive capacity, sensitivity, and exposure to climate change can allow for more informed policy decisions. The preparation for the accelerating climate change is essential so as to keep human society within the threshold of green, where we still have opportunity to control the situation. In fact, we are now passing from low-intensity intervention period to approaching the high intensive intervention period which is in red. Only by more preparedness like monitoring the climate and climate-induced change and preparing contingency plans with increasing intensity can we stop from stepping into risky part. Sustainable management is not a choice but a must if we want to survive in the future.

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23 Integrated Natural Resource Management in India Through Participatory Integrated Watershed Management

Hrittick Biswas, A. Raizada, Suresh Kumar, and A.S. Morade

Abstract

In addition to the dynamic and inter-linked ecological and hydrological cycles that occur in nature, natural resource management also deals with various stakeholders and their needs, policies and economic implications. This resulted in the concept of integrated natural resource management (INRM), a people-centric approach evolved through the convergence of research in diverse areas such as sustainable land use, participatory planning, integrated watershed management and adaptive management. This chapter deals with two principal components of INRM, viz. soil and water. In order to reverse the process of land and water degradation, it is imperative to follow integrated soil and water management (ISWM) strategies. Such a strategy is the focal point of participatory integrated watershed management (PIWM). Watershed-based approach attempts to bring out the best possible balance in environment between natural resources and living beings as both are interdependent. This holistic approach provides an ideal tool for planning and implementation of integrated soil and water conservation measures from the highest point to the outlet of the watershed, covering barren hill slopes, marginal lands, common lands, private lands, eroded gullies and drainage lines in order to prevent the degradation of natural resources. Some examples of adoption of INRM in different parts of the country through PIWM have been provided at the end of this chapter.

Keywords

Integrated soil and water management • Resource conservation • Participatory Integrated watershed management

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23.1 Introduction

Natural resources refer to the geophysical resources of water, soil and its productive qualities, intermediate and long-term carbon stocks, biodiversity of the managed landscapes, and the stability and resilience of the ecosystem of which agriculture is a part (CGIAR 2003). Natural Resources Management (NRM) refers to the sustainable utilization of these natural resources for providing vital ecosystem services, by focussing on the interactions between people and natural landscapes. It brings together the intertwined disciplines of land use planning, water management and biodiversity conservation, and recognizes that human existence solely depends on the productivity of natural resources, which, in turn, is determined by the extent and quality of their management.

In addition to the dynamic and inter-linked ecological and hydrological cycles that occur in nature, NRM also deals with various stakeholders and their needs, policies and economic implications. Therefore, the need for a holistic approach towards NRM resulted in the concept of integrated natural resource management (INRM), which according to the INRM Task Force of the Consultative Group of International Agricultural Research (CGIAR) is "an approach that integrates research on different types of natural resources, into stakeholder-driven processes of adaptive management and innovation, to improve livelihoods, agroecosystem resilience, agricultural productivity and environmental services, at community, eco-regional and global scales of intervention and impact" (Task Force on INRM 2001). This concept has evolved in recent years through the convergence of multi-disciplinary research in areas of sustainable land use, participatory planning, integrated watershed management and adaptive management (Tulasiram and Nagesh 2014).

The basic components of INRM are shown in Fig. 23.1. It can be seen that central to the concept is "people", because any management strategy on natural resources that limits itself to the conservation or protection of natural resources without considerations given to the use of the resources by people, and how it influences livelihoods is not likely to be sustainable.

Human beings are the prime users of natural resources, and it is imperative that community people are involved in planning, implementation and execution of different measures for protection and conservation of natural resources. This has led the emergence of various participatory approaches in NRM (Catacutan et al. 2001) and decentralization of environmental governance/natural resource management based on community participation replacing top-down natural resource management (Akbulut and Soylu 2012). Going a step further, evaluation and funding agencies emphasize not only on participatory development and implementation of natural resource conservation plans, but also want participatory impact assessment wherein local stakeholders play an integral part in the assessment process, assisted by experts (Vaidya and Mayer 2014).

This chapter aims at providing the readers with an insight on the importance of INRM for sustainable production under rainfed conditions. Among the four components of INRM, discussion on biodiversity and its management is beyond the scope

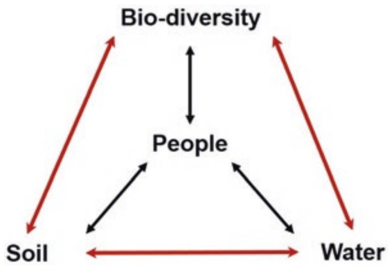

Fig. 23.1 The components of INRM

of this chapter. We therefore restrict ourselves to the integrated management of two components, viz. soil and water, and how it can be practically achieved through the active involvement of the fourth component, i.e., people through a participatory integrated watershed approach.

23.2 The Urgent Need for INRM in Present-Day Indian Agriculture

Available estimates show that, in order to meet the demands of the growing population in India, production of cereals must increase at 2% per annum and that of oilseeds at 0.6% per annum; and the overall agricultural growth rate must exceed 4% per annum (Mandal et al. 2014), and most of the production increment could be realized from rainfed agriculture (Sharma 2011). Around 57.8% of the rural households in India depends on climate-vulnerable agriculture (GoI 2008, 2014), with a high probability of negative impact of climate change (Venkateswarlu and Rao 2013). Further, the excessive dependence on and over-exploitation of forests for fuelwood, fodder, timber, paper, etc., by the ever growing human and livestock population triggers irreversible degradation of forests (Babu and Nautiyal 2015), inevitably followed by land and water degradation. Therefore, some major issues stemming from the above are: (a) augmenting productivity of crops and cropping systems (mostly from rainfed agriculture), (b) mitigating natural resource degradation in the wake of climate change, (c) managing surface and groundwater water management judiciously and (d) increasing fodder production for animals.

23.3 Rainfed Agriculture and INRM

Rainfed agriculture has been identified as a major opportunity in raising overall agricultural growth and meeting food security in India (Sharma 2011; Lenka et al. 2015). The unified approach to increase crop productivity and INRM, as discussed in the previous section, is expected to pay rich dividends in rainfed agriculture (Planning Commission 2011). India ranks first in rainfed agriculture globally in both area (86 M ha) and the value of produce (Sharma 2011). Rainfed regions in India contribute substantially towards food grain production including 44% of rice, 87% of coarse cereals, 85% of food legumes, 72% of oilseeds, 65% of cotton and 90% of minor millets (Srinivasa Rao et al. 2015). Overall, the rainfed areas occupy nearly 58% of cultivated area, contribute 40% of food production and support 40% of human and 60% of livestock population of India (Venkateswarlu and Prasad 2012), and are critical to food security, equity and sustainability. Given that cultivation of rice (41%), coarse cereals (82%), pulses (84%), oilseeds (72%) and cotton (64%) predominates in rainfed regions (GoI 2015), the role of rainfed agriculture will be vital in meeting the future demand for food grains, which is estimated at 345 million tonnes by 2030 (CSWCRTI 2011). This implies that the average productivity of food grains needs to be substantially increased from the current level of 2.10 t ha^{-1} (GoI 2015) to about 2.75 t ha^{-1}, assuming that the net sown area is almost constant. About 50% of India's total cultivated area would remain rainfed in spite of realizing the ultimate irrigation potential, estimated at 139.5 M ha (Planning Commission 2009), which means that, about 40% of the additional supply of food grains needed to match future rise in demand will have to be met by rainfed agriculture. This necessitates the need of increasing the productivity of rainfed areas from the current 1 to 2 t ha^{-1} in the next two decades (Venkateswarlu 2011). This assumes a larger significance considering the fact that crop response or incremental yield per unit of nutrients tends to be lower with increasing fertilizer use per hectare, and the evidence for soil organic matter depletion being a prime cause for declining soil health and soil productivity is mounting (Sharda et al. 2010).

Rainfed agriculture, particularly in the arid and semi-arid regions, is highly susceptible to adverse impact of climate change due to the limited options available for coping with variability of rainfall and temperature (Rao et al. 2011). India is one of the most vulnerable countries to climate change (FAO 2002), and among different sectors, climate-dependent agriculture is relatively more vulnerable. While the patterns of droughts, floods and tropical storms are becoming more unpredictable, rural livelihoods are largely affected by the effects of water stress, land degradation and loss of biodiversity. Marginal and small farmers are more prone to climatic extremes as they have limited resources at their disposal; and as a result they are compelled to overstrain already eroding lands in order to survive. The increased pressure on the land causes a further decline in soil fertility and production, and thus aggravates poverty. This circular, cause-and-effect relationship between rural poverty and environmental degradation is conspicuous, therefore degradation must be directly addressed to ensure sustainable development in rainfed areas. The challenge is to transform rainfed farming into more sustainable and productive systems through efficient use of natural resources. The next two sections cover two vital natural resources, viz. soil and water, with respect to their current status and management needs. Biodiversity, the third important resource is not included in this chapter, as it is believed that soil and water management are among the key precursors of biodiversity management, and that abundant biodiversity is the end product of efficient soil and water management.

23.3.1 Soil

Soil is a finite and non-renewable natural resource. It takes between 200 and 1000 years for 2.5 cm of topsoil to form under cropland conditions (Pimentel et al. 1995). Fertile soils have always been the mainstay of prosperous civilizations, and great civilizations have fallen in the past because they failed to prevent the degradation of soils on which they survived (Diamond 2005). The inherent productivity of many lands has been dramatically reduced as a result of soil erosion, accumulation of salinity and nutrient depletion (Scholes and Scholes 2013). Soil erosion is largely attributed to faulty land use practices, rapid deforestation rates, overgrazing, poor irrigation and drainage practices, inadequate soil conservation measures and climate change (Irshad et al. 2007). Per capita land availability is shrinking throughout the world, threatening food security, particularly in poor rural areas and triggering social and economic crisis. The rate of land degradation has progressed at an alarming rate. An estimate shows that the rate of land degradation in rainfed areas in India in the 1990s is likely to have proceeded at more than twice the rate observed in 1980s, basically on account of soil erosion from runoff (Reddy 2000).

In India, about 120.72 M ha area is affected by various forms of land degradation (Maji 2007), of which 82.57 M ha is accounted for solely by water-induced soil erosion in excess of 10 Mg ha^{-1} $year^{-1}$, followed by chemical degradation (24.7 M ha). In an assessment made under the soil loss tolerance limits project (Mandal et al. 2009) for the whole country, about 40.3 M ha of the total geographical area can tolerate a soil loss up to 5 t ha^{-1}, which calls for immediate protection strategies. As per an estimate by Indian Institute of Soil and Water Conservation, Dehradun in 1983, about 5334 million tonnes (16.35 t ha^{-1}) of precious soil is lost annually, resulting into a loss of 5.37–8.4 million tonnes of nutrients, reduction in crop productivity by <5% to >50% and reduction in capacity of reservoirs by 1–2% annually (CSWCRTI 2011). Sharda et al. (2010) estimated that out of the annual production loss of 13.4 million tonnes due to soil erosion under rainfed conditions, cereals contribute 66% followed by oilseeds (21%) and pulses (13%), which underline the urgency to minimize such losses in future.

The negative impacts of soil erosion are loss in crop productivity, disruption of nutrient cycle, alteration in water and energy balances, pollution of water bodies, deterioration in water quality, reduction of reservoir capacity and natural disasters like floods and droughts. Rainfall in the semi-arid tropics (SAT) generally occurs in short torrential downpours. In these regions, it is common that rains occur with high intensity leading to high runoff and soil erosion damaging natural physical resources, agricultural crops. Most of this water is lost as runoff, eroding significant quantities of precious top soil.

23.3.2 Water

As per United Nation standards, countries with annual per capita water availability of less than 1700 m^3 are considered as water stressed and those with less than

1000 m^3 as water scarce (Cosgrave 2000). In India, per capita availability of water has declined from 5300 m^3 in 1955 to 2200 m^3 in the early 1990s against the world's average of 7400 m^3 and Asian average of 3240 m^3 (Dey 2013). It is projected to further decline to 1463 and 1235 m^3 by the years 2025 and 2050, respectively (Navalawala 2000). India would need 2788 billion m^3 of water annually by 2050 to be above the water stress zone and 1650 billion m^3 to avoid being labelled as a water scarce country (Das et al. 2014). Also, the per capita water availability in the East flowing river basin of Tamil Nadu is as low as 380 m^3, while it is as high as 18,400 m^3 in the Brahmaputra basin thereby indicating a highly uneven distribution across different regions of our country. Further, the share of agriculture in total water use may reduce from 78% at present to 72% in 2025 due to competing demands from other sectors (CSWCRTI 2011).

It is estimated that 25 and 20% area of the country receives an average annual precipitation of less than 750 mm and between 750 and 1000 mm, respectively (Katiyal 1997). The rainfed area contributes only 45% to the national food basket due to inadequate and highly erratic rainfall, while 37% of the irrigated area accounts for 55% of the total food production (Sharda and Ojasvi 2005). The current rainwater-use efficiency for crop production is low ranging from 30 to 45%; thus annually about 300–800 mm of seasonal rainfall goes unproductive, lost either as surface runoff or deep drainage. An insight into the rainfed regions shows a grim picture of water scarcity, fragile ecosystems, droughts and land degradation due to soil erosion by wind and water, low rainwater-use efficiency, high population pressure, poverty, low investments in water use efficiency measures, poor infrastructure and inappropriate policies.

It is estimated that to meet water demand by 2050, the country needs to create storage of at least 600 billion m^3 against the existing storage of 253 billion m^3, with 50.96 billion m^3 from projects under construction (CWC 2013). Katiyal (1997) estimated that out of 70 M ha-m potentially utilizable surface water resource about 24 M ha-m is available for harvesting in storage structures of which 1/4th can be harvested in ponds and tanks in rainfall zones up to 1000 mm. It would be sufficient to provide 6 cm depth of supplemental irrigation to about 60% of the rainfed area in the country. Economic viability of water harvesting and supplemental irrigation at the national level was estimated and the results show that a surplus rainfall to the tune of 114 billion m^3 can be harvested from 28.5 million ha rainfed cropped area (Rao et al. 2009). This harvested water would be adequate to provide one turn of supplementary irrigation of 10 cm depth to 20.65 and 25.08 M ha during drought and normal years, respectively. Further, water used in supplemental irrigation had the highest marginal productivity and increase in rainfed production above 12% was achievable even under traditional practices. Under improved management, an average increase of 50% in total production can be achieved with a single supplemental irrigation (Sharma et al. 2010). Thus, gap between water supply and demands necessitates harnessing of available water resources with efficient water conservation and management techniques.

It is in this context that water conservation and harvesting have been duly emphasized in the National Water Policy as well as the National Agricultural Policy of

Government of India. The mammoth task of water resources development and management on equitable basis, however, cannot be achieved without active participation of the community. It has been shown that participatory water resource development in watershed management programmes has increased biomass production and resulted in floods and droughts control, groundwater augmentation, employment generation and improvement of socio-economic conditions of the local people (Grewal et al. 1995; Samra et al. 1995). Water harvesting technology though initially devised for arid and semi-arid regions has now become imperative for subhumid and humid regions also (Verma and Tiwari 1995).

In addition to harvesting of surface water, which has a potential to increase food grain yield by 60–65 million tonnes (CSWCRTI 2011), three other inter-linked strategies can be adopted for efficient utilization of rain, ground and surface water, viz. groundwater recharge, in-situ soil moisture conservation and more crop per drop of applied water.

23.4 Integrated Soil and Water Management

Land and water degradation occur in parallel and are inter-linked. The relationships are obvious, but often these resources are still considered independently. Land and water management cannot be treated in isolation, because injudicious management or over-exploitation of one leads to the degradation of the other. Poor land and crop management strategies degrade water quality (for example, through accelerated erosion or contamination) and reduce water productivity (Molden et al. 2003; Zwart and Bastiaanssen 2004). At the extreme, complete crop failure in rainfed systems reduces water use efficiency to zero. While this is often due to temporary or seasonal drought, it is also caused by soil nutrient and carbon depletion that reduce productivity and increase drought sensitivity. Similarly, poor or injudicious management of water contributes to land degradation, by increasing erosion, salinization and water logging. Salinization of soil and water affect productive potentials, reduce water use efficiency, result in loss of high quality water to saline sinks and abandonment of previously arable lands.

For sustainable production and livelihoods, the negative trends in land and water degradation can be reversed by:

(a) Integrated soil and water management (ISWM) by adopting innovative, cost-effective and location-specific conservation technologies suited to different climatic, edaphic and physiographic conditions for minimizing losses and ensuring sustainable farming systems production;
(b) Efficient management of natural resources through conservation agriculture, horticulture and agroforestry;
(c) Judicious use of scarce water for irrigation, devising and adopting efficient water harvesting and irrigation methods, and sustainable utilization of low quality waters to reduce pressure on high quality waters and preserve land.

(d) Intensification of agricultural systems in a way that is sustainable and compatible with the needs of nature and society for ecosystem services including food production, clean water, biodiversity, carbon sequestration and resilience to climate change.

Samra (2005), Sharda et al. (2005) and Bhan (2013) reviewed the successful cases of NRM involving small-holder farmers and communities. One key feature of indigenous success stories is that land and water management are always integrated. The major challenge has always been to produce more and better food and maintain or improve critical ecosystem services without further undermining our environment. This can be achieved by the unified management of land and water sustainably to achieve higher productivity levels, husband resources for future generations, and derive livelihoods in the most equitable manner possible. These are laudable goals; yet, specific management options must focus at the level of what is practical.

23.5 Participatory Integrated Watershed Management as a Facilitator of ISWM

The unit often employed to systematically analyse the direct and indirect impacts of NRM activities is a watershed. Sustainable watershed management is the rational utilization of natural resources for optimum production to fulfill the present need without compromising the needs of future generations with minimal degradation of natural resources such as land, water and environment. As a unit of land and water management, the watershed offers immense scope to improve crop productivity—whether of rainfed crops or under small-scale irrigation—and biomass for livestock. Watershed based approach attempts to bring out the best possible balance in environment between natural resources and living beings as both are interdependent. This holistic approach provides an ideal tool for planning and implementation of integrated soil and water conservation measures from the ridge to the outlet of the watershed, covering barren hill slopes, marginal lands, common lands, private lands, eroded gullies and drainage lines in order to prevent the degradation of natural resources. Watershed approach also allows accurate monitoring of components of water balance or hydrologic cycle, sediment, energy, carbon and nutrients balances in a given ecosystem. Keeping the multifaceted benefits of watershed programmes, the Government of India has accorded high priority to the holistic and sustainable development of rainfed areas through the integrated watershed development program since the 7th Five Year Plan (1985–1990). The success of watershed management in reducing runoff and soil loss, groundwater augmentation, increased biomass production, employment generation, enhanced income and improvement in socio-economic conditions of the local community has been amply demonstrated since 1970s.

The traditional top-down approach of watershed management (since 1970s) did not pay dividends, partly because entire emphasis was given on bio-physical aspects

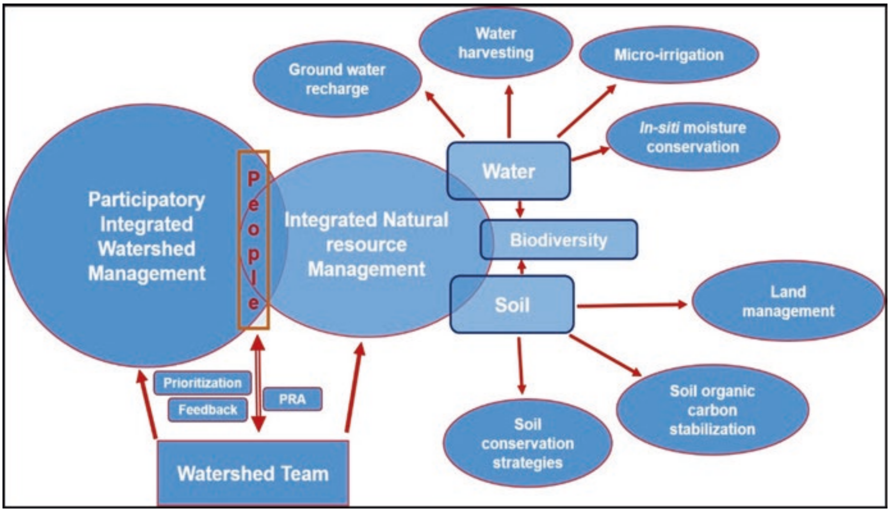

Fig. 23.2 Schematic representation of INRM contemplated through PIWM

with little focus on socio-economic aspects and community participation. It began to be widely recognized that development and management of wastelands requires a mix of bio-physical and social aspects through community participation following the bottom-up approach. Therefore, after 1994, India's four decades-old watershed management programme switched from the conventional (top to bottom) to participatory (bottom-up) mode. On these lines, participatory integrated watershed management (PIWM) programmes, with a people-centric approach (which is also the core concept of INRM) such as NWDPRA, IWDP and NAEP, were launched. Figure 23.2 is a schematic representation of INRM under the aegis of PIWM, both of which ultimately benefit the people for whom the programmes are conceived. It can be seen that INRM along with its components, i.e., soil and water are managed and conserved in a particular PIWM project by the watershed team after identification and prioritization of problems through participatory rural appraisal (PRA) through various strategies for achieving the targeted biodiversity, ultimately affecting the socio-economic conditions of the watershed beneficiaries.

Watershed development has come a long way from a catchment protection strategy in Europe and America in 1930s for downstream benefits to become an effective tool for rural development and sustainable livelihood of the watershed inhabitants in many developing countries including India in its present participatory integrated form. Past experiences have shown that resource conservation, crop productivity and income generation can be enhanced provided concerted efforts on watershed basis are made with active involvement and participation of the local community. Typically, the PIWM Participatory Rural appraisal (PRA) is conducted by a multidisciplinary team by way of interacting with the stakeholders, making them aware about the programmes and identifying the needs, problems and opportunities before implementation of the watershed project.

23.6 Examples of INRM Through PIWM in India

India has addressed the challenges mentioned in the earlier sections and made major investments in the area of watershed management through an appropriate mix of technical innovations, participatory approaches and an enabling policy environment. There are evidences of positive impacts in terms of improved soil and water conservation and agricultural productivity in normal rainfall years in regions that have been ignored in the conventional green-revolution-based rural development (Samra 1997).

In Argal watershed of Fatehpur district (Uttar Pradesh) use of rain gun to provide five irrigations to wheat as compared to the conventional four flood irrigations increased average wheat yield by 20%, besides saving 25–40% irrigation water (CSAUAT 2012). The water use efficiency in case of wheat also increased from 11.2 kg ha^{-1} mm^{-1} to 16.3 kg ha^{-1} mm^{-1} through the former technology. Check dams, bunding, staggered terraces and small *kutta crate* dams were constructed in a systematic manner thereby reducing soil loss by 20%. Renovation of one check dam increased the groundwater level of the nearby areas by 1–3 m, increased water storage and enabled the farmers of the surrounding villages to cultivate wheat with four irrigations in at least 20 ha, with yield levels ranging from 38 to 45 q ha^{-1}. Construction of a demo-farm pond with 800 cu m, with a catchment area of 6 ha, covering a group of eight farmers to provide supplemental irrigation to *rabi* crops such as mustard and wheat. Increase in groundwater recharge and creation of irrigation facilities through the renovation of existing structure and construction of earthen embankments on 50–50 participatory basis. Total number of beneficiaries under the INRM programme through which an additional area of 80 ha could be brought under irrigation was 125.

In Aganpur-Bhagwasi watershed, Patiala (Punjab) under IWDP project, impact of land levelling, bunding and terracing was positively reflected on yield of wheat, lentil, mustard and *taramira* to the tune of 20.2, 9.9, 20.2 and 8.4%, respectively, as compared to unlevelled fields (Katiyar et al. 2004). Further, contour bunding on higher slopes resulted in higher moisture retention and favourable growth conditions, thereby enhancing the survival rate and growth of fodder grasses, fruits and forest plants. The impact of various conservation measures was positively reflected on erosion control. The soil loss reduced from 12.6 Mg ha^{-1} during the pre-watershed period to 2.8 Mg ha^{-1} after the imposition of treatments. Crop Fertilization Index, which is the ratio of the total quantity of fertilizer nitrogen (N), phosphorus (P) and potassium (K) applied by the farmers to the total quantity of NPK that should be applied as per recommendations to a particular crop, increased from 0.430 to 0.645, post implementation of the watershed project. The index is a measure of the awareness created among the farmers about the positive benefits of fertilizer application on crop yields and net profits.

Three micro-watersheds in Badakheda, Rajasthan (Singh et al. 2004) were compared with respect to application of soil of water conservation measures viz., mechanical and vegetative measures (W_1), mechanical measures alone (W_2) and no-treatment control (W_3). Soil loss was reduced by 78% and 47% in watersheds W_1 and W_2, respectively (Table 23.1). Further, groundwater table increased by

Table 23.1 Year-wise runoff and soil loss under treated and untreated micro-watersheds

Year	Rainfall (mm)	Runoff % of rainfall			Soil loss (t/ha)		
		W1*	W2*	W3*	W1*	W2*	W3*
1999	180.5	10.5	16.2	32.4	20.8	26.0	46.5
2000	150.8	3.5	14.6	14.7	12.9	23.2	36.4
2001	209.8	4.9	16.9	40.8	10.6	13.1	56.6
2002	78.0	6.1	11.8	20.4	NR	NR	NR
Average	154.8	6.3	15.5	29.4	14.8	20.8	46.5

W1*: Treated with mechanical and vegetative measures
W2*: Treated with mechanical (11.3 ha)
W3*: No soil and water conservation treatments (29.3 ha)

Table 23.2 FYM and fertilizer use in pre- and post-project period in Kokriguda watershed

Crops	FYM (t ha^{-1})		Urea (kg ha^{-1})		DAP (kg ha^{-1})		MOP (kg ha^{-1})	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Paddy	0.5	4.0	18.3	51.2	13.3	37.41	–	4.5
Ragi	3.8	6.5	18.5	55.1	14.1	29.6	–	–
Vegetables	2.3	9.5	8.0	103.8	–	55.0	–	–
Average	2.2	6.67	14.9	70.03	9.13	40.67	–	1.5

0.5–1.0 m in the influence zone of water harvesting structures. Well influence and well recharge rate improved by 20% and 6%.

Soil samples were collected from 71 grid points during pre- and post-project periods in Antisar watershed (Gujarat) and analysed for various soil properties (Kumar et al. 2004). The fertility maps were prepared for the pre- and post-project distribution of nutrients in the watershed area. Organic carbon content increased from 0.31 to 0.38%. The nutrient indices computed from the grid data indicated that during the post-project period, there was slight improvement in soil fertility in terms of N and P. This was attributed to increase in usage of nitrogen and phosphorus based fertilizers in the watershed. Considering a C:N ration of 1:11 and soil weight of 2×10^6 kg ha^{-1} of top 15 cm of soil depth, the total additional nitrogen build up in the watershed worked out to be 127.3 kg ha^{-1}. This amounted to an intangible benefit equivalent to INR 2.1 lakhs for arable area of 698.6 ha.

Farmers of Kokriguda watershed (Odisha) were exposed to the importance of maintaining soil health through participatory demonstrations (Patnaik et al. 2004). Soils of the watershed are generally acidic, with low organic carbon, available N and P. Farmers of the watershed were not aware of the impact of soil fertility on crop production. As a result (Table 23.2) of the demonstrations, there was a three folds and five folds increase in the use of FYM and fertilizers, respectively, over pre-project status (2.2 t ha^{-1} FYM and 24.03 kg ha^{-1} fertilizer NPK). As a consequence, soil organic carbon content increased from 0.32% during the pre-project to 0.51% during the post-project period. Similar increases in fertility and available nutrients status including N, P and K were also observed across the watershed. Cost-effective

Table 23.3 Reduction of soil loss through conservation measures in Salaiyur watershed

Particulars	Before project	After project
Surface runoff (%)	4.5–7.2	1.3
Soil loss (t/ha/ year)	1.7–8.9	0.5–1.6

Table 23.4 Improvement of soil properties after implementation of treatments in Salaiyur watershed

	Pre-project					Post-project				
			Available nutrients (kg/ha)					Available nutrients (kg/ha)		
Crop	pH	O.C	N	P	K	pH	O.C	N	P	K
Mango	7.7	0.37	164	10	37	7.1	0.53	271	50	90
Tamarind	7.8	0.21	192	13	33	7.4	0.63	246	31	99

measures such as contour graded bunds, stone bunds, trench cum bunds, vegetative barriers, hedge rows, field bund strengthening, safe disposal structures, summer ploughing, sunken pond, diversion channels, loose boulder check dams, cross barriers and retards were constructed in Kokriguda watershed, Orissa (Patnaik et al. 2004). Bio-engineering measures were generally preferred. These interventions, carried out on a participatory mode, resulted in a substantial decline in soil loss from 38.2 to 6.64 t ha^{-1} $year^{-1}$, and runoff from 37 to 12%. There was a rise of 0.32 m water table in the open well and increase in crop yield by 15 (little millet) to 38 (upland paddy) percent. A large number of high value field crops were introduced, thereby increasing the overall diversification index from 0.68 to 0.98, and the cultivation land utilization index upswing from 0.14 to 0.20%.

During the PRA exercise conducted in Salaiyur watershed, Coimbatore (Tamil Nadu), it was informed that the weir at the outlet of the watershed used to overflow almost every year or at least during the normal rainfall year (Sikka et al. 2004). Based on the visual observations and local enquiry, peak discharge in the range of 2.0–5.2 m^3 could be estimated. The extent of runoff varied from 27 mm to 43.2 mm, which was 4.5–7.2% to the rainfall. During the project period, a peak discharge of 1.2 m^3 at the outlet was recorded with total runoff past the weir being 8.9 mm, which was 1.3% of the rainfall (Table 23.3). This suggests that most of the rain was conserved and runoff was stored within the watershed to help augment groundwater recharge (Sikka et al. 2004). Based on the runoff gauging data available at ponds/check dams, surface runoff was found to be 8–10% of the rainfall for selected rainfall events. Based on the silt deposited behind selected check dams/ponds, soil loss was estimated to vary in the range of 0.5–1.6 t ha^{-1} $year^{-1}$, which was very well within the permissible limits. There was a reasonably good establishment of mango and tamarind in watersheds after improved soil working and application of balanced dose of fertilizers thereby improving soil fertility as evident from Table 23.4.

The most classic example of participatory integrated watershed management is that of Fakot watershed in Uttarakhand. The compiled results (Samra 1997) of interventions imposed in the watershed in terms of benefits to people are shown in Table 23.5.

Table 23.5 Production and protection impact of watershed management programme during pre-project, active interventions and after withdrawal of interventions (Fakot, Uttarakhand hills, 327 ha)

Product	Pre-project (1974–1975)	Average of Interventions (1975–1976)	Average of Withdrawal (1987–1995)
Food crops (q)	882	4015	5843
Fruit (q)	Neg.	62	1962
Milk ('000 lit.)	56.6	184.8	237.6
Floriculture	Nil	Nil	120.0[a]
('000 INR)			(1994–1995)
Cash crops	6.5	24.8	202.5
Annual rearing method	Heavily grazing	Partially grazing	Stall feeding
Dependency on forest fodder (%)	60	46	18
Runoff (%)	42	18.3	13.7
Soil loss (t/ha/annum)	11	4.5	2.0

[a]Community diversified into floriculture in 1994

Table 23.6 Effect of watershed management strategies on groundwater recharge in different regions of India

Watershed	Surface-storage capacity created (ha-m)	Observed rise in groundwater table (m)[a]
Bazaar-Ganiyar (Haryana)	79.0	2.0
Behdala (H.P)	18.0	1.0
Bunga (Haryana)	60.0	1.8
Chhajawa (Rajasthan)	20.2	2.0
Chinnatekur (A.P)	5.6	0.8
GR. Halli (Karnataka)	6.8	1.5
Joladarasi (Karnataka)	4.0	0.2
Siha (Haryana)	42.2	2.0

[a]Difference between pre-project and post-project water table

Another compilation (Samra 1997) shows that the rise in groundwater table by implementation of watershed activities has varied from 0.2 to 2.0 m across different watersheds of the country, and the surface-storage created ranged from 4.0 to 79.0 ha-m (Table 23.6).

Integrated soil and water management strategies adopted in a PIWM mode in various locations and farming situations in the IWDP led to reduction of runoff and soil loss which was estimated to range from 9 to 24% (Table 23.7). Soil loss was reduced and brought within acceptable limits. As a consequence of increased moisture retention and water availability, farmers in these watersheds were able to increase crop production and also began to diversify to more profitable crops to enhance their income. In general there was a significant shift from subsistence farming using a large number of crops to the cultivation of lesser number of crops but

Table 23.7 Reduction in runoff and soil loss in IWDP watersheds due to interventions

	Surface runoff (%)		Soil loss (t/ha/year)	
Watershed name	Pre-project	Post-project	Pre-project	Post-project
Aganpur–Bhagwasi	48.5	24.0	12.6	2.8
Antisar	33.0	16.0	0.40	0.04
Bada Khera	30.0	10.0	40.0	10.0
Bajni	25.4	16.3	12.1	8.3
Kokriguda	36.8	12.4	38.2	6.6
Salaiyur	4.5–7.2	1.3	1.7–8.9	0.5–1.6

with higher yields along with the cultivation of remunerative crops. The crop productivity index (CPI) increased by 12–45% (depending on location and type of crops) and on average the CPI changed from 0.50 to 0.64 after project implementation. Crop diversification index (CDI) increased from 6 to 79% in nearly all watersheds. Further, as a consequence of land levelling, field bunding, safe disposal of runoff water and increase in area under cultivation, cultivated land utilization improved from 2 to 81% and as measured by the cultivated land utilization index (CLUI) which increased from 0.26 to 0.33 by the end of the project.

23.7 Prospects and Issues in PIWM

The concept of PIWM, based on the recommendations of the Hanumantha Rao committee (GOI 1994), has been pivotal to the success of INRM in many watershed programmes (Sharda et al. 2005; Sharda 2005). We have discussed the role of PIWM in facilitating ISWM to achieve sustainability in crop production and management of natural resources. Though biodiversity management has not been discussed in this chapter, sustainable management of soil and water inevitably leads to rich biodiversity in the watersheds as evident from crop yields, soil health and abundant vegetation. In spite of the phenomenal success achieved by the adoption of PIWM, there have been some issues related to peoples' participation (Bhan 2013). Some of the major constraints identified in involving people in the planning or watershed development phases are non-availability of time (Kumar et al. 2004), difficulty in collective decision making due to vested interests, huge bio-physical and social variations within the watershed, and fragmented land holdings (Joshi et al. 2004a), distance from land holdings and market, and inequity of watershed benefits due to up and downstream externalities (Gupta et al. 2016).

Although substantial public and external funds are being spent on watershed development in different parts of the country, the economic and environmental impacts of the program and the sustainability of the interventions have been questioned (Joshi et al. 2004b; Reddy et al. 2007). Interestingly, Samra and Sharma (2009) observed that even after spending nearly INR 192,510 million for watershed development, the results have not been very "visible" and in many cases the entire watershed had reverted back to its pre-project phase, due to lack of focus on sustainable livelihood opportunities, absence of interest by communities in natural resource conservation and missing links on issues of sustainability of production systems.

While there have been numerous instances of natural resource augmentation through PIWM, it is imperative that the benefits are sustained for posterity. We have already witnessed the dark side of green revolution in terms of over-exploitation of natural resources and yield stagnation. The same can happen if we do not protect the benefits accrued from the watershed management programmes. The following paragraphs explain the phenomenon of human complacency, and clearly call for putting appropriate post-withdrawal strategies in place while formulating watershed management programmes.

The impacts of watershed interventions in India are directly linked to increased groundwater availability for irrigation (Joshi et al. 2004b), and there is a preconceived notion among stakeholders that watershed projects lead to rapid groundwater recharge, which motivates them to invest in bore wells without waiting for substantial amount of rainfall to replenish groundwater. Shivamurthy et al. (2006) reported that the net irrigated area increased by 26% and yield of water from wells increased by 70% as a result of soil and water conservation interventions. As a consequence, the area devoted to water-intensive crops like paddy and sugarcane increased from 13 to 45 ha while it declined in areas outside the watershed. They also reported inequity in access to groundwater in the watershed.

The availability of freewater for irrigation in some states is shifting cropping patterns in favour of water-intensive crops, which should not be encouraged. Typical examples are that of cultivation of sugarcane, Bt cotton, high yielding maize cultivars in areas spread over North Karnataka, Maharashtra, western part of UP, Telangana and Andhra Pradesh. This leads to unregulated access and use of groundwater which accelerates its depletion, especially under low rainfall situations. Mondal et al. (2014) reported that farmers had their own strategies to cope with drought by diversifying farming practices, borrowing, migration and finally the sale of assets and livestock. It is therefore evident from the above discussion that unsustainable extraction of groundwater offsets the potential impact of ISWM in watershed programmes, particularly in the low rainfall zones of the country.

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Monitoring and Assessing Anthropogenic Influence on Soil's Health in Urban Forests: The Case from Moscow City

24

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Abstract

Urbanization dominates current land-use change with important environmental consequences worldwide. Urban green zones including parks and urban forests provide key functions and services for city dwellers. Most of the urban forests' functions, including biodiversity maintenance, supporting carbon and nitrogen cycles and climate mitigation are supported by soil. Therefore, urban forests' soil health and its vulnerability to anthropogenic influence need thorough investigation. In the chapter the anthropogenic influence on soil health was studied for the unique forest experimental station located in Moscow and exposed to urbanization

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for more than a century. Changes in soil physical (bulk density), chemical (nutrients' and heavy metals' concentrations and mobility), and biological features (amount of ammonifiers and soil nitrogen-fixing activity) resulted from continuous urbanization and anthropogenic load were studied. Urbanization effect on soil health and functions was examined through comparison of the recent soil features to the historical data obtained at the same experimental sites prior urbanization, whereas anthropogenic influence gradient was studied based on the proximity to the roads and residential blocks. Substantial anthropogenic influence on soil features, their time dynamics, spatial variability, and profile distribution was found. Urban forest soils' contamination with heavy metals was more than ten times higher compared to the non-urbanized counterparts. Concentration of heavy metals increased and nutrients' concentration decreased from the forest core to the boundary zones. Over-compaction of forest topsoil was observed in proximity to the pathway network. Negative changes in soil chemical and physical features resulted in substantial decline in soil health and depletion of important soil functions, like support of a nitrogen cycle. The observed negative trend in forest soil health, resulted from urbanization and anthropogenic pressure, highlights importance to develop strategies of sustainable urban development, integrating green zones into urban areas.

Keywords

Urbanization • Urban forests • Soil functions • Heavy metalls • Recreational load • Over-compaction • Functional zones

24.1 Urbanization and Urban Soils

Urbanization is among the main current land-use change trends, having important consequences for environment and society. More than half of the world's population live in cities and the proportion of urban population is projected to 70% by 2050 (Seto et al. 2012; FAO 2013). This tendency generates an ever increasing concern to scientifically evaluate and understand the consequences of overpopulation and urbanization (Buhaug and Urdal 2013). Environmental consequences of urbanization include changes in energy and matter fluxes, alteration in vegetation and soil cover (Svirejeva-Hopkins et al. 2004; Pickett et al. 2011). Urban ecosystems are exposed to different anthropogenic disturbances, including air and water pollution, biodiversity loss, and soil degradation (Stroganova et al. 1997; Walsh et al. 2007; McKinney 2006). Negative environmental changes increase morbidity and mortality risks, decrease the birth rate and generally quality of life. The deterioration of human living conditions and growth of various diseases have been observed recently in different cities. For example, infant morbidity increased 20% and adult morbidity (mainly diseases of cardiovascular system) increased 150% during 1985–1990 as a result of rapid urbanization in Moscow city (Stroganova et al. 1997; Mosina et al. 2014). The infant mortality rate in the Russian capital is twice that of London, Rome, and Toronto, and three times the rate of Tokyo and Madrid. The mean life span of a Moscovite is 7–8 years less than residents of Vienna, Paris, or Tokyo (Stroganova et al. 1997). Decrease of the total quality of life in large cities is also reported by the urban audit in European Union (EU 2013). Although the negative environmental consequences of urbanization are very important, recent studies highlight the potential of urban areas to provide and support important services, such as decreasing and treating storm water runoff (Xiao and McPherson 2002; Pataki et al. 2011), mitigating air pollution (Nowak et al. 2006; Dadvand et al. 2015), and enhancing carbon and nitrogen storage (Lorenz and Lal 2009; Raciti et al. 2008; Morel et al. 2014). If urban ecosystems are degraded or, on the contrary, perspective for provisioning important functions and services, is mainly distinguished by implemented land management strategies, including soil management practices.

Urban soil is a specific phenomena, exposed to permanent direct and indirect anthropogenic influences. Direct influences include sealing, over-compaction, pollution, and salinization (Burghardt 1994; Stroganova et al. 1998; Craul 1992). Indirectly human influences urban soils by altering soil forming factors and soil functioning (Prokofieva and Stroganova 2004; Pickett et al. 2011; Vasenev et al. 2012). For example, climatic soil forming factor, changed by urban heat island effect (Landsberg 1981; Oke 1973, 1987), can increase mineralization of soil organic carbon through raised microbiological activity and respiration rate (Kaye et al. 2005). Introduced urban vegetation, including ornamental trees and shrubs, lawns, and flower-beds also result in alteration of carbon, water, and nutrient fluxes in comparison to natural counterparts (Zircle et al. 2011; Vasenev et al. 2015). Relief is another soil forming factor, exposed to alteration through leveling and accumulation of technogenic sediments (Alexandrovskiy et al. 1998; Vasenev et al. 2013a). Parent materials for urban soils' formation include natural and technogenic sediments, cultural layers, and even buried horizons of natural soils. These parent materials have a very diverse chemical composition including toxic substances, sewage, industrial and domestic wastes (Prokof'eva et al. 2007; Dolgikh and Aleksandrovskii 2010).

In result, urban soils possess features, processes, and functions which are different from natural ones and are mainly driven by men. Averaged urban soils' features [i.e., aggregated in reviews of Lorenz and Lal (2009, 2015), Prokof'eva et al. (2013), and Vasenev et al. (2015)] include the following: (1) vertical growth of topsoil layers and predominantly "synlithogenic" soil formation process; (2) short time periods for soil formation, resulting in the primitive stages of pedogenesis, typical for some (mainly topsoil) horizons; (3) specific chemical features, caused by dust deposition and anthropogenic disturbances and including alkaline pH, contamination with heavy matters and hydrocarbons; (4) altered physical features, including high bulk density and stoniness; and (5) specific microbial community both in terms of biodiversity and total biomass. Urban soils' carbon stocks and fluxes are comparative or surpassing those for zonal soils, however, high spatial heterogeneity and temporal variability is often reported (Vasenev et al. 2013b, 2014). Spatial heterogeneity and complexity of urban soils in terms of their profiles, morphological, chemical, and biological features constrain assessing urban soils' quality.

24.2 Quality and Health of Urban Soils

Historically, soil quality was examined and assessed directly through agronomic features (i.e., pH, nutrient content, bulk density) (Bastida et al. 2008). For example, the depletion of soil organic carbon stocks is traditionally used as a basic indicator of soil degradation (Nortcliff 2002; Mairura et al. 2007). Individual agrochemical features are included into integral indexes (Bastida et al. 2008). For example, soil ecological index considers different climatic characteristics and parameters of soil fertility (Karmanov et al. 2002; Savich et al. 2003). Agroecological index describes the relationship between soil productivity and local chemical and physical properties in comparison to zonal standards (Vasenev and Bukreyev 1994). Agrochemical indicators implemented to assess cropland soils are less applicable for urban soils, where "human-oriented" functions like, for example, runoff purification, air quality control are more relevant than soil fertility per se. Therefore, sanitary quality indicators, assessed through comparison of pollutants' concentrations to the corresponding health thresholds, are widely used to assess urban soil's quality. Following health thresholds assumes excluding possible negative effects of urban soils on the citizen's health. For example, the threshold limit value, maximal permissible concentration (MPC), which is the most widely used health threshold in Russia and post-soviet countries, is a universal standard regulated at the federal level. It refers to the maximal pollutant's concentration secure for human health (HS-2.1.7.2041-06 2006a). MPC was further developed to the estimated permissible concentration (EPC) considering differences in soil buffer capacity (HS-2.1.7.2511-09 2006b).

Chemical indicators of soil quality are sometimes criticized for weak correspondence with soil living phase. Soil biological parameters recently got widely accepted, since they are strongly linked to majority of soil processes and functions and are very sensitive to anthropogenic influence (Nortcliff 2002; Gavrilenko et al. 2011; Vasenev et al. 2012; Creamer et al. 2014). Consideration of soil biological features as more sensitive and informative indicators of soil quality resulted in the concept of soil health (Karlen et al. 1994, 1997; Trasar-Cepeda et al. 1998; Gil-Sotres et al. 2005). Soil health is widely used in soil monitoring and assessment in Europe, USA, and Russia, whereas the set of implemented indicators vary between the countries and projects (Höper 1999; Stenberg 1999; Sparling et al. 2004). For example, reduction of soil microbiological activity, measured by microbial biomass content and soil respiration, is recommended by the Russian Ministry of Environment and Natural Resources to assess soil ecological status and identify disaster zones (Vinogradov et al. 1993). Microbial biomass estimated by substrate-induced respiration, basal respiration, and the contents of soil enzymes are used in soil monitoring practices in Germany and the Czech Republic (Höper and Kleefisch 2001; Dilly 2001). Microbial biomass content determined by the fumigation-extraction method, basal respiration, contents of soil enzymes, intensity of nitrogen mineralization, and the population density of earthworms is considered in Switzerland (Maurer-Troxler 1999; Mäder et al. 2001).

Biological indicators of soil quality vary from rather simple and straightforward such as microbial biomass carbon (Wardle 1992; Nannipieri et al. 2002; Ananyeva et al. 2008) or microbial respiration (Ananyeva 2003; Castaldi et al. 2004; Vasenev et al. 2012) to more complex indicators of genetic profiles (Ritz et al. 2009). Soil microbial carbon indicates the soil's performance as a habitat for microorganisms. Soil microbial communities contribute to biodiversity and gene reservoirs (Andrews et al. 2004; Blum 2005; Dobrovolsky and Nikitin 2012). The relation between soil microbial carbon and microbial respiration defines the microbial metabolic coefficient (qCO_2), which is widely accepted as a relevant indicator of the state of microbial soil communities and ecosystem disturbance (Anderson and Domsch 1989; Dilly et al. 2003; Bastida et al. 2006). More advanced biological indexes are coming from biotesting and biodiagnostics approaches, when soil quality is related to the state and behavior of soil organism or test-objects.

24.3 Monitoring and Assessing Soil Health in Urban Forest

Soil health is influenced by anthropogenic disturbance and therefore comparative analysis of soil health parameters in different functional zones in a city (i.e., industrial, residential, and recreation) is usually included in urban soil's assessments. Most human exposure to urban soils occur in parks, green spaces, and landscapes used for recreational purposes (Cheng et al. 2015). Therefore, the focus on improving health conditions in urban environments through the conservation, growth, and optimization of green areas continues to be an area of ever increasing scientific interest. Urban green zones, including urban forest, parks, and green infrastructure, perform important functions and ecosystems services and at the same time are very vulnerable to anthropogenic disturbance. Therefore, assessing soil health of urban green zones is a key part of urban monitoring.

Urban forest is a specific quasi-natural ecosystem, which keeps many natural features (e.g., zonal tree species and soils types), however, is exposed to anthropogenic pressure. Urban forests are responsible for major ecosystem services, including biomass production, preserving biodiversity, maintaining soil quality, air purification, and mitigation climate change (MA 2003; TEEB 2010). These services are highly valuable in urban environment and some of them are unique for green zones and can't be performed by other urban landscapes (Gómez-Baggethun and Barton 2013). Most of these services are directly or indirectly related to urban forest' soils. Features and functions of urban forest soils are usually considered as undisturbed standards, to which soils located in other functional zones are compared (Ivashchenko et al. 2014). At the same time, urban forest soils are more vulnerable to anthropogenic pressures in comparison to artificially constructed urban soils (Smagin 2012; Smorkalov and Vorobeichik 2015). It is important to study and understand the key factors influencing the formation and sustainability of woody plants in urban ecosystems in order to develop eco-technological methods for mitigation of a negative anthropogenic impact. Hence, long-term comprehensive studies of forest and forest-park ecosystems of a city and environmental monitoring are essential. Studying urban forest soils is important to understand possible urbanization effect on soil health, therefore data of continuous long-term monitoring of soil health in urban forests is highly relevant. Different soil characteristics can be related to various anthropogenic and non-anthropogenic soil forming factors (Pouyat et al. 2009a). At the scale of a metropolitan area, physically unaltered soil areas are more common to find, moving from the highly developed urban region to suburban and rural areas (Effland and Pouyat 1997). Nevertheless, these physically unaltered soils can be influenced by changes in environmental factors that are related to urban land uses at a significant distance from the urban centers (Pouyat et al. 2008; Carreiro et al. 2009). At finer scales such as the densely populated area of a city or town, and the even finer scales of a district, sector or household, the characteristics of soils are associated more with anthropogenic factors rather than non-anthropogenic ones. Moreover, at the smaller scale of observation it is more likely a particular human activity or change can be correlated with a specific soil response.

The aim of the chapter is to review anthropogenic pressures and their influence on soils' features, functions, and soil health in urban forests and to present relevant methodologies to monitor and assess soil health as an integral indicator of anthropogenic disturbance. A unique urban forest experimental station with more than 150 years land-use history was studied in Moscow city. The forest was conquered by the Moscow city expansion during this period and it is currently more than 10 km inside the city boundary, whereas it was almost 15 km outside the city a century ago. Long-term monitoring data collected during the decades of research in the forest experimental stations provides a unique opportunity to analyze and assess anthropogenic influence on soil health in urban forest.

24.4 Material and Methods

24.4.1 Research Area

The forest experimental station (FES) is a unique forest area of about 248.7 ha (55°50′ N and 37°14′ E) in the north-west of Moscow, and is a distinctive recreational and scientific study area (Fig. 24.1a, b) (Naumov 2009). FES has a rectangular shape (2.8 × 1.6 km). North of the station, there are fruit and vegetable stations that are part of the K.A. Timiryazev Moscow Agricultural Academy (MAAT), a park with a large pond. In the east there are fields, farms, and residential houses, and in the west there are new multi-story buildings, a metallurgic plant, and the Moscow–Riga railway. South of the station, there are new buildings. The length of the FES border is 8.3 km, more than half of which is located close to the city infrastructure.

Vegetation of FES is diverse in composition and structure of tree plantations (age ≥100 years), corresponding to a plant subzone of mixed coniferous-deciduous forests (pine forests with a complex admixture of oak, linden, maple) making it a

Fig. 24.1 Location of forest experimental station (FES) in Moscow: Northern Administrative District (**a**) with surrounding residential buildings (**b**)

"scientific laboratory and a treasure trove of knowledge". More than 100 years ago experimental plots for regular taxation studies were laid out in FES (Turskiy 1993), which makes this area very useful for research. Wood plantations of FES play a significant role in effective reclamation and landscaping. In 1940 the FES area was declared as a conservation area and now it has the status of a specially protected natural territory of Moscow (Naumov 2009).

The FES is comprised of almost 235 ha (91%) of tree plantations (woods), 22 ha (9%) of unforested areas, and about 10 ha of roads and glades. For nearly a century, conifers dominated among the FES tree plantations. However, by 1962 conifers' area was reduced to 51%. Today, pine tree plantations dominate by 34%, oaks occupy about 27% of the area, and minor components—such as birch, larch, and linden take over about 21, 14, and 2%, respectively. Conifers (pine, larch, fir-tree) occupy 48% of the forest area and deciduous occupy less than 30%. The mean age of tree plantations in the FES is 81 years old with pine, oak, and birch median ages being 100, 86, and 57 years, respectively. In the second tier of the forest, there are Norway maple (48%), larch (29%), oak (16%), birch, elm, ash, and ground cover, which is represented by more than 80 species of flowering plants, including meadow and weed vegetation (Mosina et al. 2014).

The FES territory is in a temperate continental climate zone. The mean annual rainfall is 551 mm per year (monitoring from 1879 to1962) with maximum rainfall in July and August, and minimum in January and February. Precipitation in the form of snow, on average, is 24% of the annual amount of precipitation. Snow cover in the field and forest (height is approximately 50 cm) remains on average for 139 and 181 days, respectively. The mean annual temperature is 3.8 °C, humidity is 79% (66 and 87% in May and November–December, respectively) (Naumov 2009).

The FES territory is located in the southern part of the slope of the Klin–Dmitrov Ridge. It is represented by a moraine (hilly) plain, which is also the watershed between the Moscow and Yauza rivers. The area is composed of quaternary rocks (moraine) with Jurassic clays lying underneath (depth of 20–22 m). Sod-podzolic soils (Eutric Podzoluvisols) on the moraine loam covering the top of the moraine hill and gentle slopes dominate the FES territory (70% of total area). Sod-weak and medium podzolic soils on moraine sand and sandy loam give 25%, whereas the rest 5% of the area are covered by sod medium and heavily podzolic soils, and low- to medium-sod gley soils on loams, located at the bottom of the main slope.

24.4.2 Methods

24.4.2.1 Sampling Design

Our research focused on assessing the impact of anthropogenic influence from urbanization (e.g., heavy metals soil contamination, soil compaction) on the soil features and health at the FES. Therefore, the experimental sites of about 50 × 100 m^2 with various tree plantations were selected at different distances from residential areas of Moscow city (Table 24.1). Closer to urban areas, more than 3000 people annually visit the FES territory (especially on weekends), which is considered as a high anthropogenic load. Further from urban areas, the anthropogenic load is lower (less than 3000 people). The Krasnaya Polyana and Istrinskiy forest sites were selected as undisturbed controls due to their remote location from the industrial facilities and highways. Table 24.1 shows the basic composition of the tree plantations, their dominance, and status indicators, including the height and diameter of the trunk. Soils of the experimental sites are acidic (pH_{KCl} 4.0–4.25), with different amounts of total nitrogen (0.14–0.25%) and highly variable in organic carbon concentrations (2.35–8.85%) (see Mosina et al. (2014) for detailed description). The composite samples (n = 5, center and corners) were taken from mineral topsoil (0–10 cm) at the experimental plots. Samples belonging to different genetic horizons of the soil profile within 10 cm depth were aggregated. Five to seven trees were selected on the experimental plots. The soil' samples were collected along the perimeter of the projection of the upper branches of trees with 7–10 duplicates in order to reduce the anisotropy of a phytogenic field. Selected samples were thoroughly mixed and further analyzed.

24.4.2.2 Soil Chemical and Biological Analysis

Physical, chemical, and biological features were measured in the collected soil samples. The total concentrations of heavy metals were determined using an X-ray fluorescence analyzer (model TEFA—6 W Orteke company, USA). The concentrations of mobile forms of heavy metals were analyzed with a Perkin-Elmer atomic absorption spectrophotometer (model AAS450/RS-5100, air-acetylene flame type) based on the Zyrin et al. (1985) method. To determine the degree of heavy metal toxicity, sequential chemical leaching was performed. This method reveals the degree of mobility as the elements increase bond strength during the leaching process. To differentiate mobile forms the following extracts were used: 1N $Ca(NO_3)_2$ (exchange forms), CH $_3SOONH_4$ with pH 4.8 (available forms), 1N HCl

Table 24.1 General information (localization, composition of forest stands, height of the trees (H) and diameter of the trunks (D), soil physical and chemical properties) of the research areas: the FES experimental sites at different distances from the urban areas (sites 1–7) and Istrinskii and Krasnopolyanski forests, considered as undisturbed controls (sites 9 and 10, respectively)

				Forest stands							
Site	DS[a] (m)	Texture	Soil density (g cm^{-3})	Tree dominants (age, year)	Composition[b]	H (m)	D (cm)	State[c]	N_{total} (%)	pH_{KCl}	C_{org} (%)
1	7.5	Loam	0.6–0.8	Pine + Linden (80)	5P5L1B	26	30		0.16	4.10	2.09
2	20	Loam	0.6–0.8	Oak (70–80)	5O2B1P	17	22		0.19	4.25	2.36
3	75	Loam	1.4–1.8	Oak (70–80)	7O2B1P	17	22	–	0.19	4.20	5.09
4	75	Sandy loam	1.4–1.8	Pine + Birch (90–110)	5P5B1O	19	30	+	0.25	4.15	3.90
5	75	Sandy loam	1.4–1.8	Oak (100–120)	9O2B1P	18	27	–	0.21	4.25	3.06
6	500	Sandy loam	0.6–0.8	Oak (100–120)	6O3B1P	18	32	+	0.14	4.15	2.22
7	500	Loam	0.6–0.8	Oak (70–80)	8O1B1P	23	35	+	0.16	4.20	2.72
8	500	Sandy loam	0.6–0.8	Pine + Birch (90–110)	5P5B3O	24	32	++	0.15	4.00	2.56
9	5000	Sandy loam	0.6–0.8	Pine + Birch (80)	5P3B2S	19	30	++	0.19	4.10	2.35
10	5000	Sandy loam	0.6–0.8	Oak (80)	5O2B1S1P	26	30	++	0.25	4.20	2.85

[a]*DS* distance from residential zone
[b]*P* pine, *L* linden, *B* birch, *O* oak, *S* spruce
[c]++, healthy; +, depressed; −, disintegrated

(potentially available forms), and 6N HCl (very stable forms). Soil nitrogen-fixing capacity (actual and potential) was determined with acetylene gas chromatograph Chrome-4. The phosphorous concentration was determined according to Maslova's method and Al concentration according to Sokolov (Vorobyova 1998). Their forms were determined similarly to the methods used for heavy metal content described above. Soil bulk density was calculated using conventional weight approach (Shein et al. 2000).

Microbiological studies were carried out in the fresh soil samples during different seasons according to the conventional method (Zvyagintsev 1991). Cultures were planted with maximum distribution at a certain depth in four replications. Total amount of ammonifying bacteria was determined by placing soil suspensions on meat-peptone agar (MPA, pH 7.0–7.2). Spore-forming bacteria were grown by inoculating pasteurized soil suspension (for 10 min at 75–80 °C) in the medium consisting of equal portions of MPA and WA (wort agar) (pH 7.0–7.2). Microorganisms that consume mineral forms of nitrogen, including actinomycetes, were placed on starch ammonia agar (SAA, pH 7.2–7.4), fungi grew on acidified wort agar (WA, pH 5.0–5.5). Species identification was carried out by Krasilnikova and Bergey approach. Number of ammonifiers (MPA), and bacteria using mineral nitrogen (SAA), was measured by growing them on solid media (Zvyagintsev 1991). Experimental results are expressed as mean with ± standard deviations.

Biological features were considered to investigate soil health, whereas some physical (bulk density) and chemical (heavy metals' concentrations) were used to assess the anthropogenic influence.

24.5 Results and Discussion

24.5.1 Heavy Metals in the FES Soils

According to Pouyat et al. (2010), research using urban–rural gradients suggests that soils of remnant forests are changed by environmental fluctuations happening along the gradient. Forest soils within or near urban areas often receive high amounts of heavy metals, organic mixtures, and acidic compounds via atmospheric deposition.

There are scarce data about the heavy metals content and dynamics in the FES soils. Therefore, this study aimed to obtain such information and develop methods of assessing changes in the soil HM content resulted from anthropogenic influence for the last century of intensive urbanization. It turned out that at the beginning of the last century soil samples had been collected from the FES experimental (forest taxation) plots, and stored in the soil and agronomic Museum of V.R. Williams (Moscow). In these and recently collected soil samples, the HM content was analyzed. It was found that the concentrations of Pb, Zn, and Cu in the soil of modern oak and coniferous-birch stands averaged 125, 145, and 92 mg kg^{-1}, respectively, whereas in the "old" stands the HM concentrations were 23, 4, and 9 times lower, respectively (Fig. 24.2).

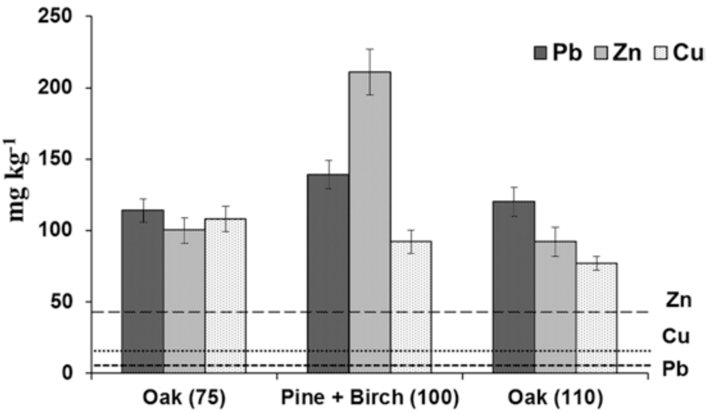

Fig. 24.2 Heavy metals (Pb, Zn, Cu) content of modern and "old" (dotted lines) sod-podzolic soil (0–10 cm) in different tree plantations (age, years)

Furthermore, a century ago the concentration of Pb was about 1.5 times less than its clark number (clark Pb = 10 mg kg^{-1}), with copper—at two times less (clark Cu = 50 mg kg^{-1}), and zinc almost equal (clark Zn = 20 mg kg^{-1}). Thus, in the modern soil the Pb concentration increased in 23 times compared to the background value. The modern and "old" soil samples have different densities (1.4–1.8 and 0.6–0.8 g cm^{-3}, respectively, with a difference of 1.8 times). Therefore, in the modern soil, which is compacted due to a high anthropogenic load, the Pb concentration is elevated. Urban expansion of the last century with corresponding anthropogenic influences resulted in dramatic increase of soil pollution with HMs.

The substantial negative effect of the anthropogenic pressure on the chemical of urban forest's soils was confirmed by the analysis of HMs concentrations over the urban-natural gradient. An anthropogenic load (at different distances from the urban highways) has a tremendous effect on the HM content in the FES soil of different forest stands and age (time passes from establishment). The results show that Pb concentrations in the soil of the old oak stands (age 110 years) located further from the city roads were almost half of those located closer to the roads. In the soil of the young oak stands (75 years) the Pb concentrations were only 25% less. In the soil of the pine-birch stands, proximity to the highways also led to an increase in Pb concentration (on average by 45%) compared to stands from further away (Fig. 24.3). The Zn and Cu concentrations in the soils increased with distance from a pollution source (i.e., urban highways). In the old oak soils, proximity to the highway "promoted" the accumulation of Zn in the soil by 36% and Cu in almost seven times, respectively, in the young oak—by 14% and ten times, and in the pine with birch soils—more than 2 and 2.5 times, respectively. Therefore, an anthropogenic influence resulting in increased HM concentrations had a clear tendency to strengthen nearby residential blocks, road, and infrastructure and decreased close to the forest core (Fig. 24.4).

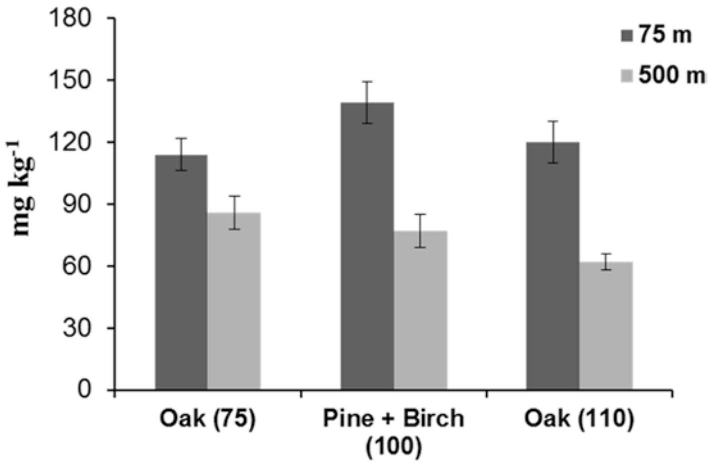

Fig. 24.3 The lead (Pb) concentration in the sod-podzolic soil (0–10 cm depth) of the different FES tree plantations (age, years) at the distance of 75 m and 500 m from the urban highway

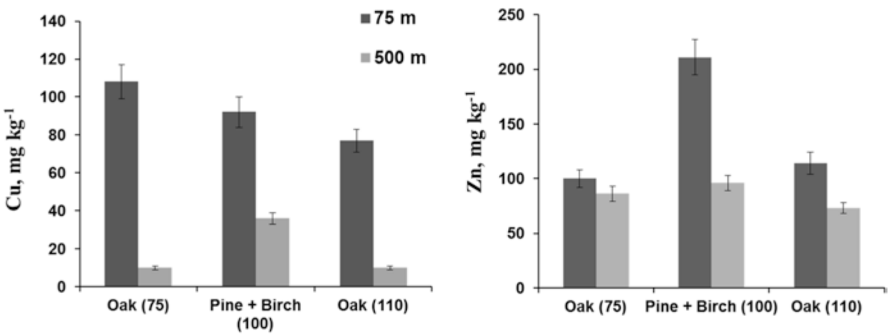

Fig. 24.4 The copper (Cu) and zinc (Zn) concentration in the sod-podzolic soil (0–10 cm depth) of the different FES tree plantations (age, years) at the distance of 75 m and 500 m from the urban highway

Not only spatial, but also even the profile distribution of HMs in the experimental plots was affected by the anthropogenic influence. The Pb concentration in the soil profile of the FES stands distributes differently depending on an anthropogenic load. The highest lead concentration was found in the upper mineral layer of the humus-accumulative horizon (A_1). It was 3–7 times higher than in the illuvial horizon (Table 24.2.). In the soil with high anthropogenic load (near urban highways), the topsoil Pb concentration was 50%, 25%, and 45% higher than that in the plots with the low anthropogenic load for oak and pine-birch forests, respectively. In the alluvial horizon (B) with a high anthropogenic load, the Pb concentration was

Table 24.2 The distribution of lead (Pb) in the soil profile of the different FES stands at low and high anthropogenic load

Dominant (age, year)	Horizon (cm)	Pb, mg kg^{-1} soil Low (500 m)	High (75 m)
Oak (110)	A_1 (0–10)	62.2 ± 4.1	120.0 ± 10.4
	A_1^1 (10–20)	21.4 ± 2.0	45.1 ± 4.0
	A_1A_2 (28–32)	16.1 ± 1.8	24.3 ± 2.0
	A_2B (45–55)	14.0 ± 1.6	19.8 ± 1.3
	B (70–80)	20.0 ± 2.0	26.4 ± 2.1
Oak (75)	A_1 (0–12)	86.1 ± 8.1	114.0 ± 8.0
	A_1^1 (12–30)	26.3 ± 2.0	49.1 ± 3.8
	A_1A_2 (35–45)	15.0 ± 1.6	21.0 ± 1.9
	A_2B (55–60)	5.1 ± 0.6	15.1 ± 1.1
	B (98–104)	12.1 ± 1.4	18.1 ± 1.0
Pine + Birch (100)	A_1 (0–6)	77.0 ± 7.8	139.0 ± 10.4
	A_1^1 (6–24)	32.3 ± 2.8	91.2 ± 7.1
	A_1A_2 (30–40)	19.4 ± 1.5	54.4 ± 4.3
	A_2B (50–55)	6.0 ± 0.6	31.6 ± 2.7
	B (76–83)	16.0 ± 1.4	42.1 ± 3.1

greater compared to the B horizon with a lower anthropogenic load. Hence, a high anthropogenic load on the soil is expressed by its proximity to a pollution source and increase in its bulk density leads to a significant Pb concentration in a soil profile, which was also observed at the experimental fields. Therefore, it may be concluded that continuous urbanization and corresponding anthropogenic influence result in substantial pollution of urban forest soils with HM in time, space, and over profile.

24.5.2 Potassium and Aluminum Concentrations in the FES Soils

Some elements (e.g., calcium, magnesium, potassium, sulfur, nitrogen, and phosphorus) decrease the toxic effects of heavy metals (antagonists), while others (e.g., aluminum, boron, fluoride, copper, and zinc) increase the effects (synergists) (Gaad and Griffiths 1978; Mengel and Kirkby 1978; Scheckel et al. 2013; Henry et al. 2015). As such, the concentration of the essential nutrient potassium (K) (antagonist) was evaluated at different anthropogenic loads in the FES stands soils. Aluminum (Al) concentration was also measured as a representative of synergists. The concentrations and proportions of different forms (not readily available, available, and exchangeable) of potassium were studied in the soil of the FES. Most of the potassium was found to be exchangeable (available for plant uptake). In the upper layer (A_1), 62–83% of the total K is in an exchangeable form (Table. 24.3).

Table 24.3 The concentration of the different forms of potassium (1—not readily available, 2—available, and 3—exchangeable) in the humus-accumulative horizon of sod-podzolic soil of the FES at different distances (DS, m) from a source of pollution and its density

Site	DS (soil density, g cm^{-3})	Dominant (age, year)	Horizon (cm)	Potassium, mg kg^{-1} soil			
				HCl (1N) [1]	CH_3COONH_4 [2]	$Ca(NO_3)_2$ [3]	1 + 2 + 3
6	500 (0.6–0.8)	Oak (110)	A_1(0–10)	10 ± 1	17 ± 3	133 ± 11	170 ± 1
			A_1^1(10–24)	13 ± 3	7 ± 2	54 ± 4	74 ± 9
7		Oak (75)	A_1(0–12)	11 ± 2	15 ± 2	120 ± 13	146 ± 2
			A_1^1(12–30)	6 ± 1	8 ± 1	35 ± 5	49 ± 5
8		Pine + Birch (100)	A_1(0–6)	21 ± 2	20 ± 3	136 ± 15	177 ± 91
			A_1^1(6–24)	11 ± 1	8 ± 2	51 ± 5	70 ± 7
5	75 (1.4–1.8)	Oak (110)	A_1(0–4)	34 ± 3	61 ± 1	100 ± 10	149 ± 15
			A_1^1(4–22)	7 ± 1	4 ± 0	32 ± 4	43 ± 5
3		Oak (75)	A_1(1–6)	21 ± 2	16 ± 2	60 ± 7	79 ± 11
			A_1^1(6–23)	5 ± 1	5 ± 1	29 ± 3	40 ± 4
4		Pine + Birch (100)	A_1(0–6)	24 ± 2	27 ± 3	113 ± 12	164 ± 18
			A_1^1(6–21)	8 ± 1	12 ± 1	38 ± 4	57 ± 6
2	7.5 (0.8–1.0)	Oak (110)	A_1(0–9)	18 ± 2	12 ± 1	121 ± 14	151 ± 17
			A_1^1(9–23)	10 ± 1	7 ± 1	49 ± 5	65 ± 7

The concentration of available K in the A_1 horizon of the oak stand soil (110 and 75 years old) and the sum of all its forms is higher at a distance of 500 meters from city roads compared with results obtained at a distance of 75 m. In the pine-birch stands, a relationship between the K concentration and the distance from the roads is less clear (136 and 113 mg K kg^{-1}in soil at 500 and 75 m, respectively). At the bottom layer of the humus-accumulative horizon (A_1'), the concentration of the exchangeable K is lower in comparison with the top. The depletion of K due to an anthropogenic load is more pronounced in the upper 10 cm of the mineral layer. This reduction is especially more noticeable in the oak stands rather than in the pine-birch stands. A reduction of K in soils leads to nutrient deficiency and attenuation in plants. Therefore, the pine-birch plantations are less susceptible to the K depletion in the soils than the oaks stands.

Aluminum in low concentrations is necessary for plant growth, but at elevated levels it can become toxic (Mosina et al. 2014). Moreover, its mobile forms are more toxic, and in acidic conditions ($pH < 5$), plants can easily uptake it in the form of $Al(OH)_2^-$, $Al(OH)^{2+}$. A high Al concentration in the soil reduces availability of many elements (phosphorus, calcium, magnesium, potassium, nitrogen) for plants and enhances their uptake of heavy metals (Foy et al. 1978). Two forms of Al were investigated in this study extracted by hydrochloric acid and salt [$Ca(NO_3)_2$]. In the humus-accumulative horizon, the concentration of the inactive Al fraction (1N HCl) varied from 143 to 812 mg kg^{-1} and the mobile fraction [$Ca(NO_3)_2$] varied between 23 and 241 mg kg^{-1}, which is 7–56% of the total soil Al concentration (Table 24.4). However, a correlation between the concentration of Al in the soil and an

Table 24.4 The concentration of Al, its non-mobile (HCl) and mobile [$Ca(NO_3)_2$] forms in the sod-podzolic soils of the FES oak and pine-birch plantations at different distances a source of pollution (DS, m) and recreational load (soil compaction, SC)

Site	DS (SC, g cm^{-3})	Dominant (age, year)	Horizon (cm)	Al, mg kg^{-1} soil	
				HCl (1N) [1]	$Ca(NO_3)_2$ (1N) [2]
2	7.5 (0.6–0.8)	Oak (110)	A_1 (0–9)	307 ± 34	172 ± 22
			$A_1{}^1$(9–23)	593 ± 61	124 ± 16
1		Pine + Birch (110)	A_1 (0–10)	812 ± 90	218 ± 22
5	75 (1.4–1.8)	Oak (110)	A_1 (0–4)	317 ± 33	103 ± 12
			$A_1{}^1$(4–22)	400 ± 46	164 ± 9
3		Oak (75)	A_1 (1–6)	143 ± 17	72 ± 9
			$A_1{}^1$(6–23)	392 ± 44	133 ± 18
4		Pine + Birch (100)	A_1 (0–6)	432 ± 54	101 ± 16
			$A_1{}^1$(6–21)	466 ± 53	208 ± 22
6	500 (0.6–0.8)	Oak (110)	A_1 (0–10)	546 ± 66	84 ± 9
			$A_1{}^1$(10–24)	656 ± 76	139 ± 15
7		Oak(75)	A_1 (0–12)	289 ± 31	23 ± 4
			$A_1{}^1$(13–30)	493 ± 54	128 ± 14
8		Pine + Birch (100)	A_1 (0–6)	489 ± 49	80 ± 10
			$A_1{}^1$(6–24)	599 ± 62	241 ± 27
10	5000 (0.6–0.8)	Oak (75)	A_1 (3–9)	714 ± 81	163 ± 15
9	5000 (0.6–0.8)	Pine + Birch (75)	A_1 (4–19)	686 ± 69	78 ± 8

anthropogenic load is not found. A proportion of the mobile Al in the investigated stands increased with intensification of an anthropogenic load (distance, compaction of soil) (Fig. 24.5). At the bottom layer of the humus-accumulative horizon (A_1'), the proportion of the mobile Al fraction also increased with an increasing anthropogenic load (Fig. 24.6), but this trend is not as pronounced as at the top.

Thus, intensification of an anthropogenic load in a soil leads to an increase in a proportion of the mobile Al (mainly in the upper humus horizon), which may indicate a deterioration of plant nourishment and overall conditions of the stands in the studied recreational area.

24.5.3 The Soil Density in the FES Tree Plantations Soils at Different Recreational Loads

Soil over-compaction determines water-air, temperature, redox, and biochemical modes in soils. Thousands of people visit the FES territory per day, and it is considered a high recreational load. Many forest areas of the FES have a network of trails. The wood plantations of these areas are depressed (dieback) with no growth, undergrowth, and underbrush. Due to a high recreational load, soil compaction takes place, especially in the upper layers. In this study, compaction of the soil at the tree plantations was examined based on different anthropogenic load. It was found that

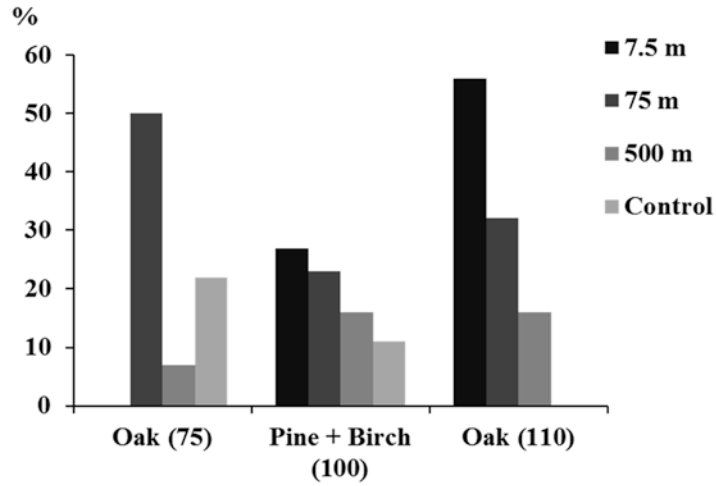

Fig. 24.5 Percentage of mobile Al form in topsoil (A_1 horizon) of the stands (age, years) due to different anthropogenic load

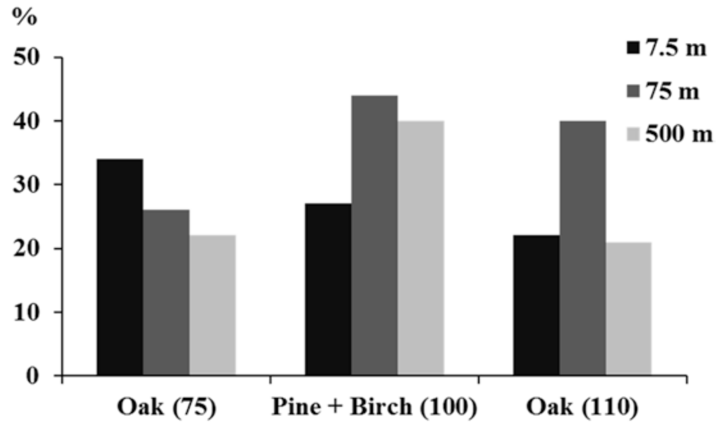

Fig. 24.6 Percentage of mobile Al form in subsoil (A_1' horizon) of the stands (age, years) due to different anthropogenic load

a high anthropogenic load (proximity to the urban roads, high traffic areas) results in increased soil compaction by 30–50% as compared to the analogues at a lower load (see Fig. 24.7).

The soil density of the upper three layers (0–3, 3–7 and 7–11 cm) under different anthropogenic loads and in different seasons over the year (spring, summer, fall) was also investigated. In the soils with low anthropogenic loads (# 9 and 10), the density of the layers was 0.7–0.9 g cm^{-3}, which almost did not change during the seasons (Table 24.5.). In the soils with low anthropogenic loads (# 6–8), the

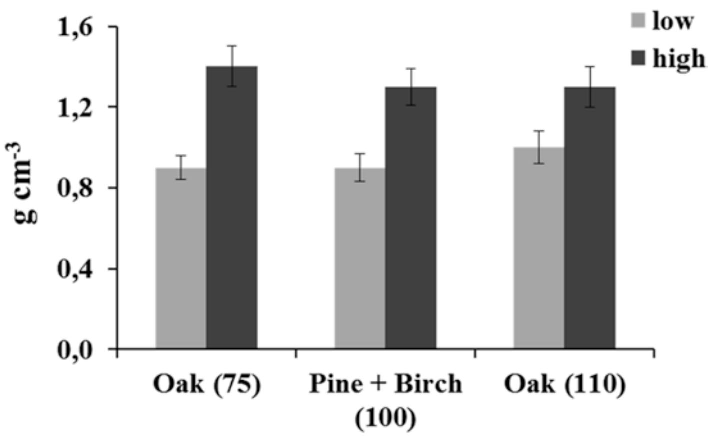

Fig. 24.7 The bulk density of the FES soil (0–10 cm) of the tree plantations (age, years) with low (500 m from the traffic) and high (75 m) anthropogenic load

increased density of the top 3 cm layer was observed in comparison to the underlying prototype (May). In September, the density of this layer was reduced while the density of the lower layer (7–11 cm) increased. A high anthropogenic load leads to significant compaction of the upper (0–3 cm) layer, especially in July and September, and mostly in the oak plantations. The increased load led to a reduction in the amount of CO_2 emissions of soils in three times in the mature oak plantations, 25 and 34% of young oak and pine-birch stands, respectively. Temperature of the soil at a high anthropogenic load was on average higher (no grass cover) than at a lower load. Humidity was lower at a higher anthropogenic load. Microbial activity of the soil (one of the main sources of CO_2) is assumed to be suppressed at a higher anthropogenic load (Table 24.6).

24.5.4 Effect of Soil Compaction on the Concentrations of Mobile Forms of Heavy Metals at FES

Environmental pollution, in particular soil contamination, is caused by elevated concentrations of heavy metals and their mobile forms (Zyrin et al. 1985). Mobile forms are readily soluble and labile forms of heavy metals. Mobility of heavy metals depends on soil properties, such as organic matter content, texture, Ca and Mg concentrations. However, there is scant data on impacts of soil compaction on heavy metal mobility. In the soil (A_1 horizon) at a high anthropogenic load total Pb concentration increased almost 2, 1.3, and 1.8 times for mature and young oaks and pine-birch stands, respectively, in comparison with those at a low load (Fig. 24.7). This trend is also observed in the A_1' horizon. Furthermore, the concentration of the mobile forms of lead (1N HNO_3extraction) in the studied soil layers showed significantly higher (3–6 times) values at a higher anthropogenic load. Hence, an increase

Table 24.5 Seasonal dynamics of the soil density (SD, g cm^{-3}) and moisture (M, %) in the forest stands under low and high anthropogenic loads

Site	Dominant (age, year)	Soil layer (cm)	May (06)		July (23)		September (18)	
			SD	M	SD	M	SD	M
Very low								
9	Pine + Birch (80)	0–3	0.7	22	0.7	24	0.7	22
		3–7	0.7	22	0.8	25	0.7	18
		7–11	0.82	24	0.9	28	0.7	18
10	Oak (80)	0–3	0.7	24	0.7	24	0.8	23
		3–7	0.8	24	0.8	25	0.8	21
		7–11	0.8	25	0.9	26	0.9	21
Low								
6	Oak (110)	0–3	1	28	0.9	30	0.6	26
		3–7	0.7	27	0.9	20	0.8	25
		7–11	0.6	25	1.2	21	0.9	25
7	Oak (75)	0–3	1.1	24	1.1	24	0.6	25
		3–7	0.7	23	0.9	23	0.7	23
		7–11	0.7	26	0.9	23	0.7	23
8	Pine + Birch (100)	0–3	1.1	28	0.9	20	0.6	23
		3–7	0.8	26	0.8	20	0.5	18
		7–11	0.7	20	0.8	20	0.8	18
High								
5	Oak (110)	0–3	1	22	1.5	18	1.8	19
		3–7	1	16	1.2	13	1.6	13
		7–11	1	18	1	14	1.5	11
3	Oak (75)	0–3	1.17	15	1.3	26	1.8	19
		3–7	1.02	21	1.1	23	1.6	18
		7–11	1.07	24	0.9	19	1.4	23
4	Pine + Birch (100)	0–3	1.09	23	0.9	18	1.8	20
		3–7	0.91	23	1	18	1.6	20
		7–11	0.9	20	0.9	19	1.5	16

Table 24.6 CO_2 emissions (EM), temperature (T), and moisture (M) of sod-podzolic soil (0–10 cm) of oak and pine-birch stands at the FES (mean during the growing season) at low and high anthropogenic loads

Site	Dominant (age, year)	Load	EM (mg CO_2 m^{-2} h^{-1})	T (ºC)	M (%)
6	Oak (110)	Low	284 ± 20	16 ± 1	25 ± 2
7	Oak (75)		114 ± 10	16 ± 1	22 ± 2
8	Pine + Birch (100)		128 ± 10	16 ± 1	20 ± 2
5	Oak (110)	High	85 ± 8	19 ± 1	18 ± 2
3	Oak (75)		85 ± 6	19 ± 1	18 ± 1
4	Pine + Birch (100)		85 ± 8	18 ± 1	18 ± 1

Table 24.7 The lead concentrations (Pb, * X-ray fluorescence analysis) in the layers of the humus-accumulative horizon of the soddy-podzolic soils under different FES stands at low and high anthropogenic load

Site	Site	Dominant (age, year)	Horizon (cm)	Pb, mg kg^{-1}		Pb [2]/ Pb[1] (ration in %)
				Total* [1]	HNO_3(1N) [2]	
Low						
6	6	Oak (120)	A_1 (0–10)	62 ± 4	2 ± 0.1	3
			A_1^1 (10–20)	21 ± 2	2 ± 0.1	7
8	7	Oak (75)	A_1 (0–12)	86 ± 8	6 ± 0.6	7
			A_1^1 (12–30)	26 ± 2	3 ± 0.1	10
9	8	Pine + Birch (100)	A_1 (0–6)	77 ± 8	5 ± 0.1	6
			A_1^1 (6–24)	32 ± 3	3 ± 0.2	11
High						
11	5	Oak (100)	A_1 (0–40	120 ± 10	11 ± 0.9	9
			A_1^1 (4–22)	45 ± 4	8 ± 0.5	17
7	3	Oak (75)	A_1 (1–6)	114 ± 8	18 ± 1.4	16
			A_1^1 (6–23)	49 ± 4	8 ± 0.5	20
10	4	Pine + Birch (100)	A_1 (0–6)	139 ± 10	13 ± 0.9	10
			A_1^1 (6–21)	91 ± 7	18 ± 1.0	19

of an anthropogenic pressure (the proximity of the city highways, trampling) leads to lead contamination of soils increasing its mobility, which results in a greater risk for the environment (Table 24.7.).

24.5.5 Effect of Larch Stands on the Soil Density at the FES

Currently, larch trees are being successfully introduced in the forest park landscapes of the subtaiga subzone because a larch root system contributes to the formation of soil structure, mainly due to an increase in the number of water-resistant aggregates (particles ≥0.25 mm). The results of this study have shown that the density of the soil under larch trees during the growing season was on average 0.68 g cm^{-3}, and under pine and lime-trees—higher (0.74 and 0.81 g cm^{-3}, respectively). The forest stands located on sod-podzolic sandy loam soils and dominated by larch (10 LC) were also compared to the forest stands of the same age and on the similar soil, but with moderate or minor role of larch (5 LC and 2 LC). It was found that the density of the topsoil mineral layer under the pure larch section was 1.6–2.4 times lower than the density of the soils under the mixed trees (Table 24.8.). Hence, it is reasonable to assume that larch plantations contribute less to soil compaction compared to other stands of trees. This undoubtedly has a positive environmental effect on recreational urban areas.

Table 24.8 The depth of the litter (LD), density (SD), and moisture (M) of the soddy-podzolic soil (0–6 cm) of the FES areas with different composition of tree stands (LR—larch; P—pine; O—oak; B—birch)

Site	Composition of tree stands	Age, year	LD (cm)	SD (g cm^{-3})	M (%)
A	10LR	100	5.5	0.6	22
B			5	0.42	25
C			5.2	0.37	18
D			4.5	0.56	17
E	5LR 2P 3O 1B	70	1.2	0.89	24
F	5O 2LR 3P	80	1.7	0.96	31

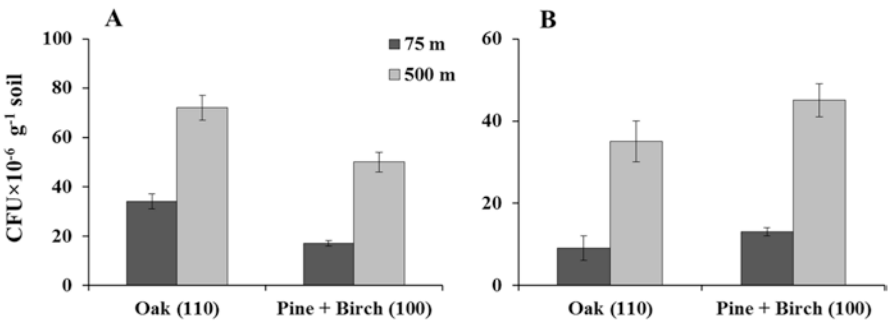

Fig. 24.8 The number of ammonifiers (**a**) and the microbes using mineral nitrogen (**b**) in the FES soil (0–6 cm) of mature (110 years old) and young (75 years old) oak, pine-birch stands at a low and high anthropogenic load (the distance from the urban highways 75 and 500 m, respectively)

24.5.6 Microbiological Parameters of Soil Health Under Different Anthropogenic Loads in FES

Soil biota is an essential constituent of the soil ecosystem, vigorously contributing to soil formation by modifying its physicochemical properties. Yet, not enough is known about the natural history and ecology of soil fauna, which is especially true for urban ecosystems because these systems have been studied less than nonurban ones (Pouyat et al. 2010). Through analysis of chemical and physical soil features of the urban forest influenced by urbanization assumed negative consequences for soil health on the experimental sites exposed to anthropogenic load. It was found that with an increasing anthropogenic load, the number of examined groups of the soil microorganisms of different forest stands significantly (2–3 times) reduced (Fig. 24.8). This indicates substantial negative anthropogenic influence on soil health via depletion of the microbial community and, as a result, its reduction of its overall functioning.

Table 24.9 The nitrogen-fixing activity of the soil under the FES forest stands at a very low, low, and high anthropogenic load

Site	Dominant (age, year)	Horizon (cm)	mol C2H4×10^{-9} g^{-1} h^{-1}
Very low			
10	Oak (75)	A_1 (3–19)	28.0 ± 2.5
9	Pine + Birch (80)	A_1 (0–4)	33.1 ± 2.9
		A_1^1 (4–17)	40.2 ± 3.1
Low			
6	Oak (110)	A_1 (0–10)	4.4 ± 0.2
		A_1^1 (10–24)	3.8 ± 0.2
7	Oak (75)	A_1 (0–4)	4.9 ± 0.3
		A_1^1 (4–22)	4.0 ± 0.2
8	Pine + Birch (100)	A_1 (0–6)	4.3 ± 0.2
		A_1^1 (6–24)	3.1 ± 0.2
High			
5	Oak (110)	A_1 (0–4)	3.1 ± 0.2
		A_1^1 (4–22)	2.4 ± 0.1
3	Oak (75)	A_1 (1–6)	3.6 ± 0.2
		A_1^1 (6–23)	2.9 ± 0.2
4	Pine + Birch (100)	A_1 (0–6)	3.1 ± 0.2
		A_1^1 (6–21)	2.2 ± 0.2

Another negative anthropogenic impact on soil health was evaluated judging by changes in soil nitrogen-fixing activity of different FES stands. The greatest nitrogen-fixing activity was in the soil of the humus-accumulative horizon at a very low anthropogenic load, the value of which is almost an order of magnitude greater than for low or high loads (Table 24.9.). Nitrogen-fixing activity of the soil (A_1 and A_1' horizon) under a low load was on average 40% higher than under a higher load (4.1 and 2.9 × 10–9 mol of $C_2H_4g^{-1}$ h^{-1}, respectively). This parameter is lower at a lower load in the pine-birch forests as compared to the oak one, but at a high load, there is almost no difference. Hence, an increase of an anthropogenic load on the soil under woody plants in the city leads to a “deterioration” of the microbial community activity, expressed by the reduction of its ability to consume atmospheric nitrogen, which is essential for plant nutrition.

24.6 Conclusions

Although urbanization is getting increasingly important, our knowledge of its possible consequences are still limited. Traditionally, negative anthropogenic influences are expected at the industrial and residential areas (factories, highways, infrastructure), whereas recreational zones are assumed to remain ecologically safe and stable. Apparently, this is more a belief that a reality, since the green zones of a city and especially urban forests are very vulnerable to anthropogenic influences following urbanization. The health of urban forest soils as an integral indicator of them ecosystem is soil function that is exposed to substantial negative alterations caused by anthropogenic influences.

We clearly demonstrated environmental consequences of anthropogenic influences for the unique forested area of more than 200 ha, experiencing continuous urbanization for more than a century. As a result, the bulk concentration of the contaminants (mainly heavy metals) increased more than ten times with a potential risks for human health. Anthropogenic influence also affected spatial variability of the heavy metals and their profile distribution. A tendency for increased contamination was clearly demonstrated for the areas of urban forests, adjacent to the residential blocks and street roads. Mobility of aluminum in the topsoil of these boundary areas was also higher than in the forest core. At the same time concentration of available nutrients (potassium) decreased at the disturbed sites. This is a strong evidence of "edge degradation" reported for urban forests and resulting to depletion of their environmental value.

Evidences of alterations in soil physical and environmental conditions resulted from anthropogenic influence were also found. The average bulk density in the sites adjacent to pathway network and therefore experiencing increased recreational load was one third higher than that of the undisturbed sites. Season deviations in soil bulk density were also found at the disturbed sites with higher values observed in summer period, when recreational load increased. Changes in the bulk density also affected other soil features. For example, increased mobility of lead was observed at the sites with higher soil density, which may be an evidence of a synergetic effect of different anthropogenic factors on soils features and health. Soil temperature increased and soil moisture decreased at the disturbed sites as a result of the urban heat island effect also contributing to the complex of anthropogenic factors, negatively affecting soil health in urban forest. Negative consequences of anthropogenic influence of soil health were clearly indicated by, for example, decrease of the total amount of ammonifiers' microbes using mineral nitrogen number, as well as by changes in total soil nitrogen-changing activity. Supporting a nitrogen cycle is among the key environmental functions of soils and therefore observed negative alterations can result in total depletion of soil functioning.

Decline of soil health in urban forest and total degradation of forest ecosystem in cities is a concern not only for scientists, but also for city municipalities. Urban green zones provide unique environmental and recreational services for city dwellers, which can't be substituted. The observed negative trend in forest soil health resulted from urbanization and anthropogenic pressure highlights importance to develop strategies of sustainable urban development, integrating green zones into urban areas. High soil quality shown for the native larch stands compared to mixed forest stands proposes nature conservation as a promising strategy to keep urban green zones. Urban green zones have vital importance for city dwellers of today and future therefore their natural value must be protected.

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Impacts Assessment of Municipal Solid Squander Dumping in Riparian Corridor Using Multivariate Statistical Techniques

25

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Abstract

Crumbling soil quality and reduction in vegetation plenitude are grave outcomes of open squanders dumping which have brought about growing public concern. The center of the present study is to assess the contribution of open squander dumping in riparian soil contamination and its impact on plant assorted qualities in riparian corridor of river Varuna. Surface soil sample ($n = 6 + 2$) was gathered from both the open squander dumping and control site. The assorted qualities of vegetation were learned at both sites. Significant changes were seen in the soil attributes of the dumping sites. Soils at the dumping indicated high pH, TDS and EC regime in contrast with control site. The assorted qualities of vegetation were also learned at both sites. A comparable pattern was seen in plant assorted qualities. Control site indicated differentiated assortment of plants, i.e., 12 plant species while this number decreased at the dumping sites. The principal component analysis created three significant components explaining 95.764 of the variance in the data attributable to open dumping effect. Hierarchical cluster analysis grouped six-dumping sites into three clusters having similar characteristics and source of contamination, i.e., moderate and highly polluted dumping sites.

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River Varuna • Riparian corridor • Squanders • PCA • Shannon diversity

25.1 Introduction

The threat of natural contamination has been haunting the human world since early times and is as yet becoming because of exorbitant development in creating nations (Ali et al. 2014). Municipal solid squanders (MSS) customarily termed as "refuse" or "junk" is an ineluctably foreordained byproduct of human activity. Populace development and financial advancement lead to gigantic measures of strong squanders era by the inhabitants of the urban zones (Rizo et al. 2012; Kanmani and Gandhimathi 2013). Urban MSS is conventionally engendered from human settlements, minuscule industries, and commercial activities (Singh et al. 2011). An adscititious source of squanders that discovers its approach to MSS is the squanders from healing centers and clinics (Manzurul et al. 2008). In greater part of nations most of the diminutive units don't have a particular strategy of dealing with these squanders. When these squanders are blended with MSS, they pose a threat for health and additionally they may have long term effect on environment (Pattnaik and Reddy 2009; Zharikov 2013).

In creating nations open dumpsites are regular, because of the low spending plan for squanders transfer and non-availability of trained manpower (Henry et al. 2006; Guerreroa et al. 2013). In India, open dumping of MSS is a regular practice. It additionally poses earnest threat to groundwater assets and soil (Gupta and Bishwas 2008). The defilement of soil by toxic metals can cause unpropitious effects on human and animal's health, and soil efficiency (Smith et al. 1996). In the course of the last numerous years, toxic metals have extensively harmed the soil quality and ripeness in result of expanded natural contamination from industrial, farming-based and city-based sources (Karak et al. 2013). Metals cause physiological clutters in soils as assimilation through root framework consequently impedes plant development and denies it of life (Moustakas et al. 1994). Squanders convey distinctive metals which are then exchanged to plants by various ways (Voutsa et al. 1996). Depending on the propensity of the contaminants they culminate up either in water held in the soil or leached to the underground water. Contaminants like Na, Mg, and K can alter the soil chemistry and have an impact on the organisms and plants depending on the soil for nourishment.

Diversity of vegetation is directly impacted by soil attributes. Numerous studies reveal seriousness of hazards brought about by open squanders dumping ultimately influencing the vegetation on the planet driving towards irreversible erosion trend unless the present land use pattern is checked (Phil-Eze 2010). Solid squanders pollutants serve as an external force influencing the physico-chemical attribute of soil at last contributing towards the poor generation of vegetation (Papageorgiou 2006). The contaminants, in any case, ruin normal metabolism of plants. Initially undetectable, owing to the harm to the metabolism. Visible injury appears in the aftermath (Ahmed et al.

1986). It is denying our biological community of the natural balance and bear result beyond any rehabilitation. Assessment of soil contamination becomes arduous when contaminants have a place with various sources and their products are variably appropriated (Partha et al. 2011). Chemical properties of soil serve as fundamental reason of vegetation changes (Neave et al. 1994). In plants amassing of chemical elements depends not just on their absolute content in a soil additionally on the level of fertility, acidic–alkaline and oxidative–reductive conditions, and on the presence of organic matter (Subbiah and Asija 1976). The distraction of greater intensity sometimes imperils the survival of some species and yield to low richness (Hussain and Palmer 2006). In such manner, creating nations are significantly more profound into the turmoil as having poor financial resources to redesign their disposal facilities and ended up to be more powerless against the risks of dumping for their surroundings (Hazra and Goel 2009).

India is generally confronted with rapid weakening of ecological conditions because of the traditional system of collection and dumping of strong squanders. Therefore urban squanders management has turned into a noteworthy worry in urban communities. Little endeavors have been made so as to enhance the squander collection and disposal facilities. This has some grave results going from deterioration of soil quality to lessened plant differing diversity. The present study has been carried out in 2015 and directed in order to evaluate the prevailing condition of soil physico-chemical attributes and its impact on vegetation in the riparian corridor of the river Varuna.

25.2 Material and Methods

25.2.1 The Study Area

Varanasi is an eternal city older than history, tradition, legend which portrays the spiritual and cultural heritage of India and is located on the west bank of river Ganga which is said to be one of the oldest, continuously inhabited cities in the world. In the present study, a stretch of the riparian corridor soil of river Varuna in Varanasi city was considered. The river Varuna rises at 25°27′N 82°18′E, near Malhan village of Phoolpur Tehsil, district Allahabad, flows east-to-southeast from Bhadohi, Mirzapur, Jaunpur, and finally enters in Varanasi for some 148 km and joins the Ganges at 25°19′46″N 83°02′40″E, the confluence near Adikeshav Ghat, just downstream of Varanasi.

The atmosphere of the study area is tropical monsoonal. The most reduced surrounding mean temperature was documented in November–December (9.8–24.4 °C) and most noteworthy in May–June (28.8–42.8 °C). The months of stormy season stayed warm and wet with excessive humidity. The shortest day period approximately 10 h was documented in December and longest in June approximately 14 h. Wind heading moves prevalently westerly and south—westerly in October through April and easterly and north—westerly in remaining months (Kumar et al. 2015a).

The landscape encompassing the River Varuna supports a variety of land uses together with diverse sorts of agriculture, commercial, and communal grazing, as well as domestic use in profoundly urbanized residential regions with first rate pressure. Most of the riparian corridors of river Varuna in the urban area are covered with large heap of refuse, which generated from residential, urban market dumped on open land. Varanasi City generates approximately 550 s MT urban squanders/day. An aggregate of eight inspecting sites (two control site and six squanders dumping site) were decided for gathering the data. The qualities of these destinations are given in Table 25.1 and locations are appeared in Fig. 25.1.

25.2.2 Field Sampling and Analysis

According to the objective of the study, three parallel surface soil sample ($n = 6$) from the profundity of 9 in. were gathered from the squanders transfer site located in riparian corridor of river Varuna. This site has been indicated as an open territory which is currently utilized for squanders dumping. Three parallel surface soil sample ($n = 2$) from the other areas of riparian corridor were likewise taken with a specific end goal to look at the nature of soil from dumping locales and control destinations. The gathered samples were homogenized, sealed, stored (4 °C), and brought to the laboratory for further examinations. They were air dried (25 °C), ground, sieved (2.0 mm) stored in brown glass jars at −20 °C before use (Ali et al. 2014; Sun et al. 2013).

A few investigations were performed keeping in mind the end goal to evaluate on the parameters that assess soil quality. Every soil sample was assessed for pH, EC (Electrical Conductivity), and TDS (Total Dissolved Solids) in a soil to water proportion of 1:5 utilizing a pH meter electrode (EUTECH PCSTestr 35), percentages of soil organic carbon and percentages of soil organic matter [% organic carbon × 1.729 (Von Bemmlen factor)] were assessed according to Walkley-Black acid digestion method. Soil texture using of the Bouyoucos hydrometer technique (Adeyi et al. 2014) and supplement concentrations [Magnesium (Mg), Calcium (Ca), Sodium (Na), and Potassium (K)] in the soil acid digests were measured utilizing flame photometer (LABTRONICS LT-671).

The plenitude of vegetation was likewise documented at every site with the help of field guides wherever possible utilizing 10 × 10 m quadrate technique (Kent and Coker 1992). The identity of the plant species was also confirmed through various sources (Hooker 1875–1897; Duthie, 1903–1922; Bor 1960; Kirtikar et al. 1975; Raizada 1976).

25.2.3 Statistical Analysis

Vegetation and soil data were examined through past3 (Shah et al. 2015). This software performs multivariate analysis of ecological information. It additionally offers numerous ordination and characterization strategies. The principal component

Table 25.1 Characteristic features of the study sites from January to December, 2013

Study sites		Zones	Distance from water level	Slope angle	Slope type	Remarks
Rameshwar bridge (control site)	C1	Riparian	0–35 m	20–35°	Steep	Agricultural belt
Nadesar bridge	S1	Riparian	0–35 m	10–12°	Moderate	Riparian erosion by anthropogenic activities, old municipal solid squanders dumping site at the bank of river Varuna
Chaukaghat bridge	S2	Riparian	0–35 m	10–12°	Moderate	Riparian erosion by human and animal intervention, old municipal solid squanders dumping site at the bank of river Varuna and, urban drain
Point opposite to Sarang talab drain	S3	Riparian	0–35 m	10–12°	Moderate	Domestic squanders dumping, laundry station, urban drain
Nakhi Ghat bridge	S4	Riparian	0–35 m	10–12°	Moderate	Riparian erosion during floods, human intervention, old dumping site, laundry station, urban drain
NH29 bridge	S5	Riparian	0–35 m	6–10°	Gentle	Riparian erosion during floods, human intervention, agricultural belt, heap of domestic and municipal solid squanders dumping along the river bank
Konia Ghat (sever line)	S6	Riparian	0–35 m	6–10°	Gentle	Riparian erosion during floods, human intervention, agricultural belt, heap of domestic and municipal solid waste disposal along the river bank
Adi Keshav Ghat (control site)	C2	Riparian	0–35 m	6–10°	Gentle	Human intervention and agricultural belt

Fig. 25.1 Geographical locations and photographs of control sites and the squander's dumping sites

analysis is applied to normalized soil data variables to extract significant principal components and to further reduce the contribution of variables (Kumar et al. 2015b). Cluster analysis (CA) strategy was taken after for the determination of grouping of examining destinations connected with vegetation.

25.3 Results

25.3.1 Comparative Assessment of Physico-Chemical Variables at Control and Dumping Sites

Essential descriptive statistics indicated comparative examination of physico-chemical properties of riparian corridor soils at both control and squander dumping site (Table 25.2). The mean estimation of pH at control site was 7.50 while the mean estimation of pH at dumping site was 8.33. A noteworthy contrast in the mean estimations of EC and TDS was seen in the soil of both zones. It was observed to be low in control sites while it was altogether diverse and discovered higher at dumping sites. The mean estimation for EC and TDS at control site were recorded as 197 μS/cm and 130 ppm while at dumping site they were 414.33 μS/cm and 268.33 ppm separately. Sandy clay loam of the principal soil composition was noticeable in both control and dumping areas. The mean estimation of sand, silt, and organic matter %

Table 25.2 Descriptive statistics of soil physico-chemical properties of control sites and squander's dumping sites

	Control sites				Squanders disposal sites			
Soil parameter	Mean ± SE	Min–max	Variance	SD	Mean ± SE	Min–max	Variance	SD
pH	7.50 ± 0.10	7.40–7.06	0.02	0.14	8.33 ± 0.07	8.10–8.6	0.03	0.18
EC (μS/cm)	197 ± 15	182–212	450	21.21	414.33 ± 35.15	326–532	7415.06	86.11
TDS (ppm)	130 ± 12	118–142	288	16.97	268.33 ± 24.83	212–362	3700.28	60.83
OC (%)	0.57 ± 0.04	0.53–061	0.00	0.057	0.91 ± 0.08	0.68–1.23	0.04	0.20
OM (%)	0.99 ± 0.07	0.92–1.05	0.008	0.09	1.57 ± 0.14	1.18–2.13	0.12	0.34
Clay (%)	29.9 ± 0.20	29.7–30.1	0.080	0.28	24.27 ± 0.22	23.70–24.9	0.29	0.54
Silt (%)	21.7 ± 0.10	21.6–21.8	0.020	0.14	22.53 ± 0.42	20.80–23.4	1.04	1.02
Sand (%)	48.4 ± 0.30	48.1–48.7	0.180	0.42	53.20 ± 0.42	51.70–54.3	1.07	1.03
Ca (mg g^{-1})	4.24 ± 2.0	2.23–6.24	8.04	2.84	28.68 ± 2.47	23.62–38.23	36.74	6.06
Mg (mg g^{-1})	26.12 ± 0.3	25.82–26.42	0.180	0.42	31.95 ± 1.24	27.84–36.56	9.25	3.04
Na (mg g^{-1})	0.25 ± 0.01	0.24–0.26	0.00	0.014	0.32 ± 0.01	0.28–0.36	0.00	0.03
K (mg g^{-1})	20.26 ± 0.98	19.28–21.24	1.92	1.39	17.83 ± 1.0	15.72–22.22	6.00	2.45

Table 25.3 The PCA axes explaining complete variance of the data

Axis	Eigenvalues	% of Variance	Cumulative %
1	7.417	61.807	61.807
2	2.336	19.465	81.272
3	1.739	14.493	95.764

Extraction method: principal component analysis

were noticeable lowered at control site in comparison to dumping site. The mean estimation for sand, silt, and organic matter % were 48.4; 21.7; 0.99 and 53.20; 22.53; 1.57 at control and dumping site, respectively. Higher % of clay at control site was noticeable as compared to dumping site because of which vegetation was more bounteous and show good diversity index at control site.

A noteworthy contrast in the mean estimation of Ca was observed at both sites. Table 25.2 demonstrated that the mean estimation of Ca at control site was 4.24 mg g^{-1} while at dumping site it was 28.68 mg g^{-1}. At a specific area the foundation centralization of metals in the soil emerges because of the topographical matter from which it is shaped. A little diverse of Mg mean estimation was noticed at control and dumping sites. Mg is a piece of parent rock material along these lines found in high concentrations at both regions (Ali et al. 2014). The mean estimation of Mg at control site was 26.12 mg g^{-1} while it was 31.95 mg g^{-1} at dumping site.

The mean estimation of Na was lower at control site as compared with dumping site. The mean estimation of Na at control site was 0.25 mg g^{-1} while it was 0.32 mg g^{-1} at dumping site. A lot of K can be inconvenient to plants and different species. In this way, potassium ought to be discharged to the earth in least amount. The mean estimation of K at control site was 20.26 mg g^{-1} while it was 17.83 mg g^{-1} at dumping site.

25.3.2 Principal Component Analysis of Dumping Sites

The principal component analysis was performed and pprincipal components (PCs) with eigenvalue >1 were retained. PCA was performed between sampling site and physico-chemical properties of dumping site soil extracts. Three PCs explain 95.764 (Table 25.3) of the total variance, the first component explains 61.807% of total variance and has strong positive loading on pH, EC, TDS, %OC, % OM, % clay, Ca, Mg, and Na while strong negative loadings on % silt (Table 25.4). Second component explains 19.465% of total variance and has strong positive loadings on % sand and K while strong negative loadings on % clay (Table 25.4). Third component explains 14.493% of total variance and has strong positive loadings on % silt and while strong negative loadings on % sand (Table 25.4) on dumping site soil of riparian corridor of river Varuna as shown in Table 25.4.

From PCA (Fig. 25.2), observed that S5 is affected by K, % sand, Ca, pH, and Na where as S2, are influenced by % OC, % OM, % clay, TDS, Mg, and EC. These results clearly indicate that S5 and S2 in comparison with S1, S3, S4, and S6 are highly affected with haphazard dumping of domestic as well as municipal solid squanders along the river bank are the main contributors of pollutants.

Table 25.4 Loading of variables on significant principal component of data related to the squander's dumping sites

Variable	PC1	PC2	PC3
pH	0.7928	0.2787	0.4954
EC (μ)	0.8855	−0.4385	0.1314
TDS (ppm)	0.9464	−1584	0.2728
OC (%)	0.9567	−0.0579	−0.2638
OM (%)	0.9576	−0.0564	−0.2629
Clay (%)	0.6754	−0.6255	0.2680
Silt (%)	−0.7663	−0.3263	0.5111
Sand (%)	0.3995	0.6498	−0.6438
Ca (mg g^{-1})	0.6995	0.4672	0.4953
Mg (mg g^{-1})	0.8717	−0.1968	−0.2929
Na (mg g^{-1})	0.9069	0.1734	0.1116
K (mg g^{-1})	0.0297	0.9093	0.4145

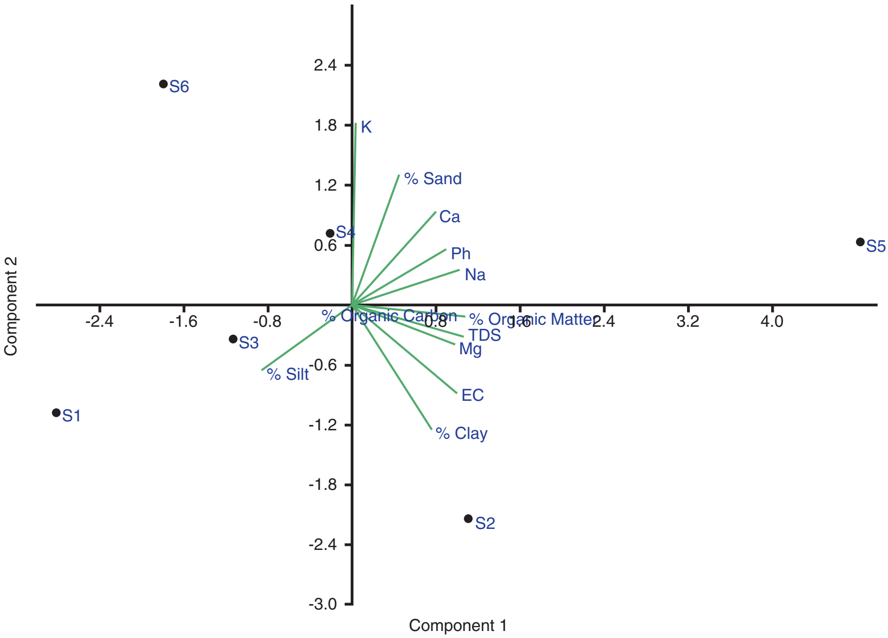

Fig. 25.2 Result of principal component analysis (PCA) for the sites and physio-chemical parameters of squander's dumping sites

25.3.3 Clustering at Dumping Sites

Cluster analysis (CA) was applied to detect spatial similarity among sites in respect to disposal site under the monitoring network (Dabgerwal and Tripathi 2016). Examining sites of dumping territory framed three particular clusters, cluster A (S2

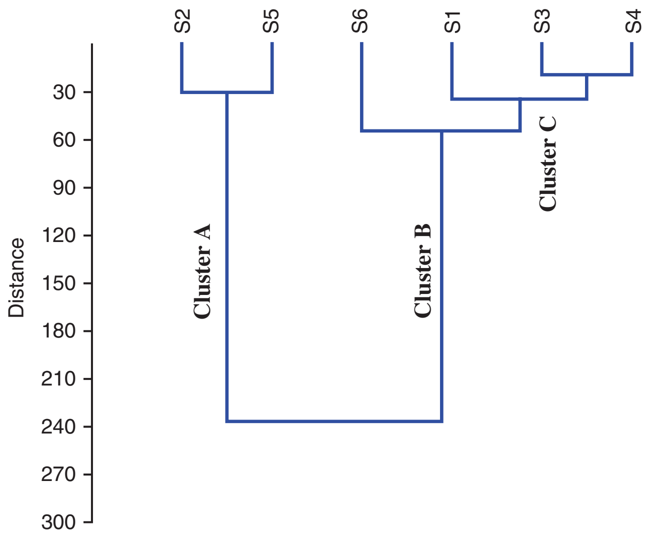

Fig. 25.3 Dendrogram showing clusters of squander's dumping sites (linkage method: Ward's method, distance measure: Euclidean)

Table 25.5 Details and distribution matrix of the plant-species recorded along the River Varuna

Plant species	Family	Habit	C1	S1	S2	S3	S4	S5	S6	C2
Borreria articularis F.N. Williams	Rubiaceae	Herbs	√	√	√	√	√	√	√	√
Chrozophora prostrate Dalz. and Gibs	Euphorbiaceae	Woolly herbs	√	√	×	√	√	×	×	√
Chrozophora rottleri (Geis) Juss	Euphorbiaceae	Herbs	√	×	√	×	√	×	√	√
Cyperus iria Linn	Cyperaceae		√	×	×	√	×	×	×	√
Cyperus kyllingia Endl	Cyperaceae	Herbs	√	×	×	×	√	×	√	√
Cyperus rotundus Linn	Cyperaceae	Herbs	√	×	×	×	×	×	×	√
Gnaphalium luteoalbum L	Asteraceae	Herbs	√	×	√	×	√	×	√	√
Nicotiana plumbaginifolia	Solanaceae	Herbs	√	√	×	√	×	√	√	√
Ranunculus sceleratus	Ranunculaceae	Herbs	√	×	×	×	√	√	√	√
Rumex acetosa L	Polygonaceae	Herbs	√	×	√	×	√	×	√	√
Rumex crispus	Polygonaceae	Herbs	√	√	×	√	√	×	×	√
Vernonia cinerea	Asteraceae	Shrubs	√	×	×	×	√	√	√	√

and S5), B (S6), and C (S1, S3 and S4) (Fig. 25.3). Distinctive physico-chemical attribute of contaminated soil at the dumping territory is one of the vital reasons behind gathering of these sites. The documented plant vegetation (Table 25.5) and its diversity (Table 25.6) are lowered at dumping sites as compared with control site.

Table 25.6 Species richness, Shannon diversity, and evenness values for the study sites

Study site	Total individuals	Species richness (S)	Shannon (H)	Evenness (e^H/S)
C1	103	12	2.40	0.92
S1	22	4	1.26	0.88
S2	15	4	2.31	0.92
S3	32	5	1.52	0.92
S4	50	9	2.14	0.94
S5	15	4	1.31	0.92
S6	43	8	1.97	0.89
C2	159	12	2.43	0.95

Major plant species observed at sites in cluster A was *Borreria articularis* and in cluster B was *Nicotiana plumbaginifolia, Gnaphalium luteoalbum,* and *Borreria articularis*. *Borreria articularis, Chrozophora prostrate*, and *Rumex crispus* are the major species in cluster C. This was because of open dumping in these territories that has brought about crumbling of soils of the region which does not support extensive number of plant species. High soluble solid concentration diminishes the water accessibility to the plants as expansion in salt concentration lessens the osmotic potential bringing about hindered plant development (Ali et al. 2014).

25.4 Discussion

Soil is a vital segment of riparian corridor and its management is the way to its quality. The vegetation status of both sites demonstrates that as opposed to arrangement, assorted qualities are suffering because of open dumping of squanders. Good number of vegetation species (12 species) was supported by soils of control sites while poor number of species was documented at dumping site. Moderately accelerated organic matter with a normal mean estimation of 1.57 was found at open dump site adding to an expansion in pH. Moreover, this is essentially because of release of interchangeable cations during mineralization of natural matter (Ali et al. 2014; Anikwe and Nwobodo 2002). Soil pH plays a major role in nutrient bioavailability, toxicity, and draining capacity into the encompassing regions. The pH, conductivity, and organic matter content on open dump sites are enormously influenced by the amount of squanders dumped (Ali et al. 2014, Tripathi and Vishwakarma 2015). A great deal more consideration is required for strong squanders management to reduce the risk from overwhelming nutrient contamination. Some variables including the properties of soil composition, pH, and contending cations in the soil that expand their versatility can bring about more plant uptake or have serious affect on soil.

25.5 Conclusions

In creating nation the management of municipal solid squanders services comes as a third need in civil duties after water supply and sanitation. Soils of the riparian corridor used as open squanders dumping are widely examined as far as physico-chemical properties of soil. Be that as it may they are under pressure from their own particular enactment to move far from the present disposal practices of open dumping to sterile area filling. Such a change is unrealistic to happen in the closest future because of constraints on money, deficiency of specialized assets, and absence of institutional plans. The principle ecological issue connected with the dumping sites is the potential risk postured to the soil. Since the squanders were directly dumped onto surface of riparian soil which debase the soil and influence vegetation wealth of the riparian territory.

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