Environ Monit Assess (2016) 188: 250
DOI 10.1007/s10661-016-5202-x

Budgeting of major nutrients and the mitigation options for nutrient mining in semi-arid tropical agro-ecosystem of Tamil Nadu, India using NUTMON model

U. Surendran · S. Rama Subramoniam · P. Raja · V. Kumar · V. Murugappan

Received: 10 September 2015 / Accepted: 19 February 2016 / Published online: 28 March 2016

Abstract Mining of nutrients from soil is a major problem in developing countries causing soil degradation and threaten long-term food production. The present study attempts to apply NUTrient MONitoring (NUTMON) model for carrying out nutrient budgeting to assess the stocks and flows of nitrogen (N), phosphorus (P), and potassium (K) in defined geographical unit based on the inputs, viz., mineral fertilizers, manures, atmospheric deposition, and sedimentation, and outputs, viz., harvested crop produces, residues, leaching, denitrification, and erosion losses. The study area covers Coimbatore and Erode Districts, which are potential agricultural areas in western agro-ecological zone of Tamil Nadu, India. The calculated nutrient balances for both the districts at district scale, using NUTMON methodology, were negative for nitrogen (N −3.3 and −10.1 kg ha^{-1}) and potassium (K −58.6 and −9.8 kg ha^{-1}) and positive for phosphorus (P +14.5 and 20.5 kg ha^{-1}). Soil nutrient pool has to adjust the negative balance of N and K; there will be an expected mining of nutrient from the soil reserve. A strategy was attempted for deriving the fertilizer recommendation using Decision Support System for Integrated Fertilizer Recommendation (DSSIFER) to offset the mining in selected farms. The results showed that when DSSIFER recommended fertilizers are applied to crops, the nutrient balance was positive. NUTMON-Toolbox with DSSIFER would serve the purpose on enhancing soil fertility, productivity, and sustainability. The management options to mitigate nutrient mining with an integrated system approach are also discussed.

Keywords Alfisols · Vertisols · Nutrient balance · Inputs · Outputs · Fertilizers · Manures · NUTMON · DSSIFER

U. Surendran (✉) · V. Murugappan
Tamil Nadu Agricultural University, Coimbatore 641 003, India
e-mail: u.surendran@gmail.com

S. Rama Subramoniam
Regional Remote Sensing Centre, ISRO, Bengaluru, Karnataka 560 037, India

P. Raja
ICAR-Central Arid Zone Research Institute, Jodhpur, Rajasthan, 342 003, India

V. Kumar
AED, Agricultural College and Research Institute, Madurai, India

Present Address:
U. Surendran
Centre for Water Resource Development and Management (CWRDM), Calicut, Kerala, India

Present Address:
P. Raja
ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Udhagamandalam, Tamil Nadu, 643 004, India

Introduction

Continuous cropping without adequate restorative practices poses a serious threat to sustainability of agro-ecosystems. The compound growth rate in yield of major crops in India is either declining or negative over the period of 1980–1981 to 2011–2012 (MoA 2013). The increase in food production must have to come from increased productivity, since horizontal expansion of cultivable area is not possible at this juncture of exploding population as that in India (Chhonkar 2003). However, at the same time, soil nutrient depletion and other forms of degradation threaten the increase in productivity (Surendran and Murugappan 2007a; Surendran et al. 2016). Previously, much research was focused on increasing the agricultural production but a gradual shift was made toward a long-term perspective considering both current and future production as well as the environmental impacts.

Soil fertility decline generally does not get the same public attention as droughts, pest infestation, etc., since it is a gradual process and not associated with catastrophes and mass starvation; it is largely imperceptible. The preservation and maintenance of fertility necessitate the investigation of nutrient element regime of the soil, which represent the life media for microbial activities as well as crop. This necessitates a regular monitoring of changes in soil fertility that occurs in the soil. For understanding the role of different process, a budgetary approach offers good tool through analyzing the turnover of nutrients in the soil-plant system at different spatial scales (World Bank 2007; IISD 2009; OECD 2010; Leip et al. 2011; Fethi and Leip 2015).

Soil nutrient balance—a review

Soil fertility decline can be accessed via expert knowledge systems, the monitoring of soil chemical properties over time (chronosequences) or at different sites (biosequences), and the calculation of *nutrient balances*, with the last one being the most used and *cost-efficient* technique (Cobo et al. 2010). Suggestions to use nutrient balances in nutrient management dates back more than 150 years but have only become accepted in farmer's practice in the last decades (Van Noordwijk 1999; Surendran and Murugappan 2010; Cobo et al. 2010). Stoorvogel and Smaling (1990) and Smaling (1998) calculated the nutrient balance for 35 Sub-Saharan African countries and reported the seriousness of nutrient depletion on future food production. Nutrient balances have been monitored by number of authors in European Union and they found that N, P, and K budgets are in the range of deficit to surplus (OECD 2010). However, it has only been in the last decade, as concerns for soil fertility decline have increased and the limitations of standard chemical fertilizers have been recognized; thus, the nutrient budgeting and balance analyses have come to the fore (De jager et al. 2001; Bekunda and Manzi 2003; Sheldrick et al. 2003; Surendran and Murugappan 2007a; Phong et al. 2011).

Understanding and modeling nutrient cycles in food and related agro-industrial systems is a crucial task. Although nutrient management has been addressed at the plot and farm scales for many years now in the agricultural sciences, there is a need to upscale these approaches to capture the additional drivers of nutrient cycles that may occur at the local, i.e., district scale. In evaluating nutrient budgets, it is important to be aware of the use of different system boundaries at regional scale (Leip et al. 2011; Phong et al. 2011). Larger-scale estimates of nutrient balance and budgeting have become increasingly influential in policy discussion related to soil fertility management and sustainable agriculture (IFPRI 1995; FAO 2004; OECD 2010).

The contamination of freshwater systems by excess nutrients results in many negative effects on the ecosystem, including anoxia, fish deaths, and the development of toxic algal blooms. Moreover, these can have adverse impacts on livestock, wildlife, and human health (Duong et al. 2012; Sutton et al. 2013). These impacts include negative effects on biodiversity, eutrophication, nitrate accumulation in waters, acidification, nitrous oxide emissions, and risks to human health due to exposure to ozone and particulate matter (Smil 2011). The agricultural sector is an important source of the N that ends up in groundwater and surface water and the atmosphere (Erisman et al. 2013; Fowler et al. 2013). Similarly, mining of nutrients will result in deficiency of nutrients and negatively affects plant growth, resulted in reduction in food grain production, and affect the sustainability of the entire ecosystem.

Some of the nutrient flows, viz., leaching, denitrification, and erosion losses, are hard to quantify on a routine basis. These flows are often estimated on the basis of (pedo) transfer functions, an approach followed for Sub-Saharan Africa (SSA) by Smaling et al. (1993) and Stoorvogel et al. (1993) and adopted and also critically reviewed by others (Smaling 1998; FAO 2003; Schlecht and Hiernaux 2004; Faerge and Magid 2004; De Ridder et al. 2004; Lam et al. 2005; Dang 2005; Khai et al. 2007; Wijnhoud 2007; Lesschen et al. 2007; Phong et al. 2011). Bassanino et al. (2011) calculated nutrient budgets according to the IRENA European methodology in Italy and found the highest nutrient surpluses (103, 39, and 95 kg ha^{-1} for N, P, and K, respectively) in the most intensely managed area. For EU27, N surplus is 55 kg N ha^{-1} year^{-1} in a soil budget and 65 kg N_2O N ha^{-1} year^{-1} and 67 kg N ha^{-1} year^{-1} in land and farm budgets, respectively (Leip et al. 2011). A comparison of nitrogen (N) budgets of agro-ecosystems is made for the EU27 countries by four models, i.e., INTEGRATOR, IDEAg, MITERRA, and IMAGE, with different complexity and data requirements. The models estimated a comparable total N input in European agriculture, i.e., 23.3–25.7 M t N year^{-1}, but N uptake varies more, i.e., from 11.3 to 15.4 M t N year^{-1} leading to total N surpluses varying from 10.4 to 13.2 M t N year^{-1} (De vries et al. 2011).

Even though there are lot of such studies across the globe, information on nutrient balance research in India is scarce. Much of the published data in India is on the national/regional level and deals only with the fertilizer inputs and random estimates of crop nutrient uptake. Researchers in the past have reported indiscriminate mining of N, P, and K from soil reserves in all the agro-climatic zones across India (Yadav et al. 2001; Katyal 2001; Kumar et al. 2001; Krishna Prasad et al. 2004; Surendran and Murugappan 2007a, 2007b) without considering the soil losses through erosion and leaching. The first phase of our study on Coimbatore District showed negative balances for N and K and positive for P indicating the mining of nutrients (Surendran and Murugappan, 2007b), and hence, the authors thought of developing a strategy for sustainable agricultural production. Keeping these facts in view, the present study was carried out to calculate nutrient budget of Erode and Coimbatore Districts of Tamil Nadu state of India, by using the decision support model "NUTrient MONitoring (NUTMON)-Toolbox" (Vlaming et al. 2001), and come out with a policy Decision Support System (DSS) and strategies for improving the agricultural productivity in the Western Zone of Tamil Nadu.

Materials and methods

Study area

The study area is comprised of two contiguous districts in the western agro-climatic zone of Tamil Nadu in the southern part of India, and site characteristics are explained in Table 1 and Fig. 1. Usually, dry climate prevails in most part of the district except western part, which has a semi-dry climate. Somayanur, Pichanur, Peelamedu, Irugur, Palathurai, Periyanaickenpalayam, Noyyal, Chavadiparai, Dasarapatti, Palladam, and Anaimalai series cover a major part of the soil series in the study area (Soil Atlas 1998). Soil map of both the districts are presented in Fig. 2 (NBSSLUP 1997). The groundwater level fluctuates annually between 3 and 15 m in wet areas and 15 and 35 m in dry areas. The main source of irrigation in the study area is by canals, tanks, and wells. Cropping pattern varies widely with the soil types and irrigation facilities.

Model description

The present study aims at application of the NUTMON concept/software tool which is developed by integrating different knowledge systems (farmers and scientific) and interdisciplinary links (soil science, agronomy, and

Table 1 Description of the study area

District	Coimbatore	Erode
Latitude/longitude	10° 10′ and 11° 30′ N and between 76° 40′ and 77° 30′ E	10° 36′ and 11° 58′ N and between 76° 49′ and 77° 58′ E
Elevation (above MSL*)	427.0 m	171.9 m
Rainfall (mm)	680	640
Major soil order	Alfisols and vertisols	Alfisols and vertisols
Population	3,472,578	2,259,608
Population density per km^2	748	397
Major crops grown—rainfed	Cotton, sorghum, pulses, and millets	
Major crops grown—irrigated	Paddy, sugarcane, banana, turmeric, maize, groundnut, variety of pulses, and vegetables	

* *MSL* mean sea level

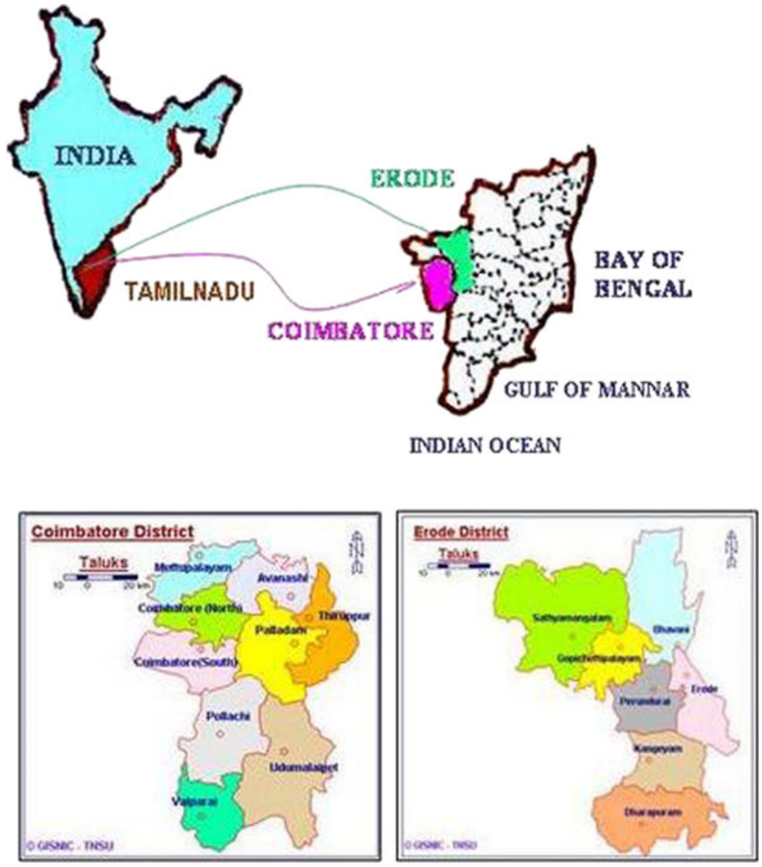

Fig. 1 Geographical location of the study area

economics) at various spatial scales (field, farm, and catchment/district level) on the assessment of nutrient inflows and outflows.

Modules

NUTMON-Toolbox module was used to calculate the nutrient flows between the units and nutrient balances. This module includes five inflows, viz., mineral fertilizers (IN1), manure (IN2), deposition (IN3), biological N fixation (IN4), and sedimentation (IN5), and five outflows, viz., harvested product (OUT1), crop residues (OUT2), leaching (OUT3), gaseous losses (OUT4), and erosion (OUT5).

Calculating inputs and outputs

Nutrient flows are quantified in three different ways, viz., by using primary data, estimates, and assumptions (Smaling and Fresco 1993; Surendran and Murugappan 2007b, 2010). Flows directly related to farm management were quantified from the primary data. Flows quantified in this way are the use of chemical fertilizer (IN1), organic inputs (IN2), farm products (OUT1), and other organic products (OUT2) and redistribution of household waste, crop residues, and farmyard manure (FYM). The resulting data fall in the category of *primary data*. These flows are quantified using the following equation:

$$\text{Flows} = \sum_{x} wd\ Prod_{x.t} \times\ fr\ Prod_x \quad (1)$$

where $wd\ Prod_{x,t}$ = amount of product x in month t kg and $fr\ Prod_x$ = nutrient content in product x in kg/kg

Information on nutrient use applied through chemical fertilizers (IN1) per ton of nitrogen, potassium, and phosphorus (NPK) was obtained from the FAI database (FAI 2010). Manure production (IN2) in each district was calculated by multiplying the per capita manure with livestock population (Murugappan et al. 1999). The quantity of manure produced by individual animal was calculated based on average body weight and by using the equation developed by Merck Vet Manual (1998). Removal of harvested produce (OUT1) entails

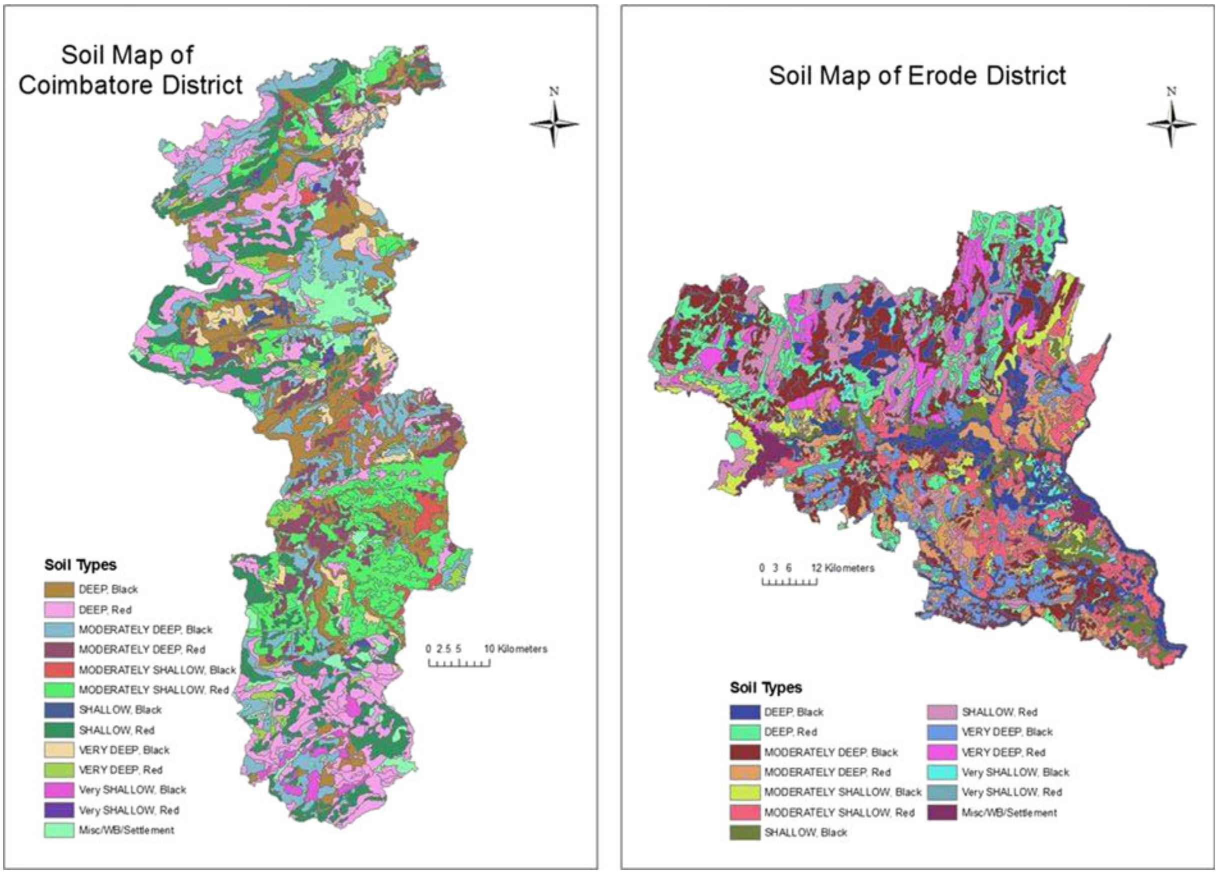

Fig. 2 Soil map of Coimbatore and Erode Districts

loss of nutrients and the quantity being determined by the average yield of the particular crop and its nutrient content. The average yield for all the crops cultivated in this district has been taken from the Season and Crop Reports (2010) published by the Government of Tamil Nadu, and by using the average nutrient content of each crop (Tandon 1997), OUT1 (nutrients exported out of the farm in crop produces) was calculated. Nutrient export in crop residues (OUT2) was calculated in a similar way by assuming that only 20 % of the generated residue is being returned directly into field as a source of nutrients and the remaining 80 % is being fed to the animals or burned as fuel (Tandon 1992).

Transfer function or models used

Atmospheric deposition (IN3), biological N fixation (BNF, IN4), leaching (OUT3), and gaseous losses (OUT4) were quantified fully on the basis of off-site knowledge using *transfer functions*, and the resulting data are estimates. Due to lack of point data on wet and dry depositions (IN3) at district level, the built-in transfer functions in NUTMON-Toolbox were used to calculate IN3 as done by Smaling et al. (1993), where nutrient input was considered as a function of square root of average rainfall in mm year^{-1}. Inflow through atmospheric deposition (IN3) in month t kg^{-1} is calculated using the in-built regression equation of NUTMON-Toolbox, which is given in Eq. (2).

Nutrient from atmospheric deposition

$$(\mathrm{Area}/10,000)\times\ (\mathrm{SQRT}(\mathrm{PrecAnnual}))\times(\mathrm{PrecMonth}_t\times\ \mathrm{Annual})\times\ \mathrm{Reg.\ Coef} \qquad (2)$$

where Area = area hectares; PrecAnnual = precipitation mm/year; $\mathrm{PrecMonth}_t$ = precipitation mm/month; Reg. Coef = regression coefficients for N, P, and K.

Non-symbiotic N fixation (IN4b) is calculated using a function relating N fixation with mean annual precipitation. A small rainfall-dependent contribution from non-symbiotic fixers was accounted as per the procedure of Stoorvogel and Smaling (1990). N input through biological fixation (IN4) is given as

$$=\text{IN4 Non-Symb}\ t\ p\ +\ \text{IN4 Symb}\ t\ p \tag{3}$$

Non-symbiotic N fixation by crops in primary production unit (PPU) p in month t kg is given in Eq. (4).

$$\text{IN4 Non-Symb}\ t\ p = (\text{Area}/10,000)\ \times\ (1/12)\ \times\ 2\ +\ (\text{PrecAnnual} - 1350)\ \times\ 0.005) \tag{4}$$

The relative contribution of symbiotic and associative N fixation to that of free living organisms to the global total was taken as 70:30 as assessed by Paul (1988). The amount of N fixed (IN4) was calculated in the present study based on this assessment. N contribution from groundwater (IN5) is considered negligible in tropical conditions (Carolien kroeze et al. 2003), and therefore, only P and K inputs from sedimentation were accounted in IN5 based on the results of Abedin et al. (1991) and Handa (1998), who, respectively, calculated 1.5 and 10 kg K year^{-1} as inputs from sediments. Leaching of N and K (OUT3) is assumed to be uniform for all soil-bound sub-systems, whereas leaching of P is assumed to be zero. The percentages of leaching for both nutrients are calculated as a function of the clay percentage of the soil and the mean annual precipitation using transfer functions based on built-in model (Smaling et al. 1993).

For N,

$$\left(\text{Mineralized}\ N_p/12\right)\ +\ \text{IN1 MinFert}\ N_{p\ t}\ +\ \text{IN1 MinOrg}\ N_{p\ t}\Big)\ \times\left(2.1\times 10^{-2}\times\text{PrecAnnual}{-}3.9\right) \tag{5}$$

For K,

$$\text{frLeach}\ K_p\times((\text{Exch}K_p\times\ 1/12)\ +\ \text{IN1 MinFert}\ K_{p\ t} + \text{IN1 MinOrg}\ K_{p\ t}) \tag{6}$$

where IN1 MinFert$_{p,t}$ is the inflow from fertilizers on PPU in month t, IN1 MinOrg$_{p,t}$ is the inflow from organic manures on PPU in month t, frLeach$_p$ is the fraction of potassium leached from PPU p, and ExchK_p is the exchangeable K in soil PPU p.

The mineralization rate to calculate OUT3 with respect to soil N was assessed in a column study. In this representative, surface soil samples were collected from the study area and packed in the column of PVC pipes having a diameter of 10 cm and height of 45 cm. The soils in the column were maintained at field capacity level. Prior to incubation, the soil was washed with distilled water and the moisture content was maintained at field capacity throughout the experimentation. The soil samples were extracted for NH_4 and NO_3–N using 2 M KCl as per the procedure of Bremner and Keeney (1985). The leachate was collected everyday and analyzed for NH_4 and NO_3–N immediately, until a static condition was reached. Based on the released quantity of NH_4 and NO_3–N, the mineralization rate of nitrogen was calculated. Total soil N was derived from collecting representative samples covering entire district and analyzed for its total N content. N mineralized ($N_{\min}$) in 0–20-cm soil layer is calculated using Eq. (9).

$$N_{\min} =\ 20\ \times\ N_{\text{tot}}\times\ M \tag{7}$$

The percentage of gaseous loss (OUT4) of N is assumed to be the same for each primary production compartment and is calculated as a function of the clay percentage of the soil and the mean annual precipitation using a transfer function (Smaling et al. 1993). Gaseous losses (OUT4) are calculated by multiplying the loss percentage by fertilizer N, mineralized soil N, and given in Eq. (10).

$$(\text{Soil N}\ +\ \text{Fertilizer N})\ \times -9.4\ +\ 0.13\ \times\ \text{frclay}_p\times\ 100\ +\ 0.01\ \times\ \text{PrecAnnual} \tag{8}$$

Erosion (OUT5) can occur in any of the primary production compartments. Soil loss (kg ha^{-1} year^{-1}) is estimated using the universal soil loss equation (Wischmeier and Smith 1978). Soil loss is converted to nutrient loss (kg ha^{-1} year^{-1}), using the total N, P, and K contents (%) of the soil and an enrichment factor.

$$\Big(\text{Soil loss}_f\times\ 1000\ \times\ \text{frSoil}_p\times\ \text{EnrichFact}\ \times\ \text{SoilFormFact}\ \times\left(\text{Area}_p/\text{Area}_f\right)\times\ \text{Cusle}_p \tag{9}$$

where Soil loss is the soil loss from FSU, frSoil is the nutrient content in soil on PPU, EnrichFact is the enrichment factor, and Cusle$_p$ is the USLE crop cover factor for PPU p.

It is not easy to derive R factor from commonly collected meteorological data. On the basis of literature data, this was set at 0.25 % for the study area. The K factor also varies with types of soil, and previous studies showed that K value ranged from 0.197 to 0.217 with 0.202 as an average. It has been found as 0.11 for Chambal ravines (Pratap et al. 1978). But for major Indian soil types, the value of K was 0.12 (Biswas and Mukherjee 1982). Slope (S) and L were determined as per the procedure of Mitchell and Brubenzer (1980). The degree of land cover also varies, and it was difficult to quantify in terms for the district. The value of C factor estimated for maize crop ranged from 0.266 to 2.528 based on the growing practices (Agnihotri et al. 1987). So, from the previous studies, an average C factor was estimated for the entire district as 1.4. Land management factor P was derived from Wenner (1981). The estimated average inherent soil fertility was used to translate soil loss data into N, P, and K losses and by multiplying by an enrichment factor to arrive at OUT5. Enrichment occurs because of the fact that the finest soil particles are the first to be dislodged during erosion and eroded soil material tends to contain more nutrients than the soil. In the present study, the enrichment factor is set at 1.5 for N, P, and K by assuming a ratio of 1:1.5 for the nutrient content of the original soil to that of the eroded soil.

Strategy development using a DSS

Nutrient depletion is the result of a net imbalance, between incoming and outgoing nutrients in farm inputs and outputs. Because many aspects of farm management influence these processes, there is a need for a “basket of technology options,” addressing the various causes of depletion. However, fertilizer being the major input, a strategy was worked out for a selected farm under the study area using a DSS named DSSIFER software (Decision Support System for Integrated Fertilizer Recommendation).

DSSIFER is a computer software, which gives crop-, site-, and season-specific fertilizer prescriptions for a specified yield target/percentage yield sufficiency based on the equations generated through soil test crop correlation studies (STCRs) which were conducted earlier in Tamil Nadu state (Surendran and Murugappan 2010).

Fertilizer prescription of a specified yield target

$$U = \alpha S + \beta F \tag{10}$$

Fertilizer prescription for percentage yield

$$Y = A\left(1 - e^{-c1b-cx}\right) \tag{11}$$

Strategies were worked out for achieving a neutral nutrient balance in the farm using DSSIFER-based fertilizer prescription rate (both organic and inorganic) for the soil fertility status of the individual crops, by taking into account the season and specific yield target.

Description of the selected farm

The irrigated farm selected for developing a strategy is located at Singampettai village in Bhavani block of Erode District of Tamil Nadu. The cultivable area of the farm is of 5.87 ha. The farm is irrigated through the well located within the farm. The soil of the farm taxonomically belongs to Ammapettai soil series (Soil Atlas 1998). The farm comprises of four farm section units (FSUs) and is divided based on the homogenous soil properties, slope, and crops grown in the farm. These FSUs consist of nine crops, viz., sugarcane, turmeric, sugarcane, brinjal, fallow, sunflower, tapioca, ratoon cane, and tapioca (Fig. 1). Nutrients for the farm were mainly through chemical fertilizers and organic manures that are met from external sources besides on-farm-generated manures. The farmer besides using on-farm manure also purchases manure off-farm and imports it into the farm. This was included as IN2a and IN2b. Besides, a part of crop residue was also directly recycled into the farm by incorporation/burning. Outflows from the farm were crop uptake (OUT1), removal in crop residue (OUT2), leaching (OUT3), gaseous loss (OUT4), and erosion loss (OUT5). Nutrient balance was worked out using NUTMON for both farmer’s practice of fertilizer application and DSSIFER-based fertilizer application.

Results and discussion

Quantification of inputs

The consumption of fertilizer in the study area has registered a spectacular growth, i.e., 30 times (0.6 to 19 MT) during the last three decades, owing to the adoption of green revolution technological packages (FAI 2010). The consumption of NPK fertilizers (IN1) in Coimbatore District were 31,986, 10,793, and 22,715 t, respectively, and in Erode district were 36,732, 11,406, and 13,422 t, respectively (Surendran and Murugappan 2007b; FAI 2010). The population of livestock and manure produced by individual animal and the nutrient potential in animal manure are furnished in Table 2. Animal manure enters the system after collection from livestock units in the farm itself (on-farm manure) or imported from nearby farms (off-farm manure). Available literature indicates that under Indian conditions, only 40 % of the total manure is used in agriculture and rest being used either as cooking fuel or wasted (Tandon 1997; Redding 1999). Therefore, out of the total potential nutrient generated from manures, the quantity that enters into the farm as nutrients (IN2) is given in Table 2.

The N, P, and K depositions (IN3) were derived from the built-in transfer functions in NUTMON-Toolbox. These values for Coimbatore and Erode Districts were 3.70 N, 0.60 P, and 2.42 K and 3.59 N, 0.59 P, and 2.36 K kg ha^{-1} year^{-1}, respectively. Land depositions of NH_3/NH_4 from the atmosphere provide about 10–20 kg N ha^{-1} year^{-1} (Derwent et al. 1988). Similar results of nutrient deposition were also reported by Sapek and Sapek (1993). They have estimated that 17 kg of N and 0.5 kg of P ha^{-1} year^{-1} were deposited in land from atmosphere. Abedin et al. (1991) and Handa (1988) have found that the annual inputs of K through atmospheric deposition exceeded 10 kg ha^{-1}. These results are in agreement with the observations made on nutrient deposition in the present study. Since the variations in climate within the study area are not considerable, the quantified deposition data was extrapolated at the district level. Non-symbiotic N fixation calculated for Coimbatore and Erode Districts were 572 and 630 t year^{-1}, respectively. Considering that the relative contribution of symbiotic and associative N fixation and non-symbiotic N fixation by free living organisms to the global total to be in the ratio of 70:30, the amount of N fixed through symbiotic fixation was arrived for Coimbatore and Erode Districts (IN4) as 1470 and 1335 t year^{-1}.

Quantification of outputs

Nutrients exported through harvested produce (OUT1) and residues (OUT2) in Erode and Coimbatore Districts have been calculated and presented in Tables 3, 4, 5, and 6. Total losses of N through leaching (OUT3) for Coimbatore and Erode Districts were found to be 8962 and 8095 t year^{-1}, respectively (28.41 and 28.30 kg N ha^{-1} year^{-1}, respectively). This calculated leaching loss of N from the system is similar to the value estimated by Bjornberg et al. (1996) (17–72 kg N ha^{-1} year^{-1}). As suggested by Dobermann et al. (1996), the leaching loss of P was assumed to be negligible, as most of the soils in the study area tend to retain/fix P. In fine-textured soils, K leaching generally does not exceed 2 kg ha^{-1} year^{-1} (Tisdale et al. 1985). However, leaching of K on acid sandy soils in southern Nigeria accounted to 16 kg ha^{-1} year^{-1} of soil-derived K and 10 kg ha^{-1} year^{-1} of surface-applied K at an application rate of 60 kg ha^{-1} year^{-1} (Omoti et al. 1983). Average K concentrations in soil water extracted by means of ceramic suction cups at 1-m depth were 0.6 mg K L^{-1} corresponding to a K leaching loss of 1.5 kg ha^{-1} year^{-1} (Askegaard and Eriksen 2000). The

Table 2 Nutrient potential from manure in Western Zone of Tamil Nadu

Livestock units	Population (nos.)		Dung/animal/year (kg)	Nutrient potential (t)					
				Coimbatore			Erode		
	Coimbatore	Erode		N	P	K	N	P	K
Cattle	419,161	603,171	4,453	7,466	1,867	5,600	10,744	2,686	8,058
Sheep and goat	308,376	741,530	277.4	642	171	385	1,543	411	926
Pig	21,640	20,330	1,058.5	126	115	115	129	108	108
Poultry	2,683,082	2,318,631	36.5	3,917	1,469	1,998	3,385	1,269	1,726
Total	-	-	-	12,151	3,622	8,098	15,801	4,474	10,817
Manure used as nutrient source (assuming 40 % of total manure)				4,839	1,443	3,223	6,320	1,790	4,327

Table 3 Nutrient export through harvested produces of Coimbatore District

Crop	Scientific name	Area	Productivity (kg ha^{-1})	Production (t ha^{-1})	Nutrient content (%)			Nutrient removal (t)		
					N	P	K	N	P	K
Paddy	*Oryza sativa*	14,110	3,595	50,725	1.12	0.34	0.81	568	173	410
Sorghum	*Sorghum vulgare*	80,284	318	25,530	1.44	0.38	0.39	367	97	100
Maize	*Zea mays*	17,272	1,125	19,431	1.62	0.41	0.47	315	80	91
Cumbu	*Pennisetum purpureum*	404	2,014	813	1.89	0.46	0.58	15	4	4
Pulses	-	30,191	450	13,586	3.36	0.37	2.12	457	50	288
Turmeric	*Curcuma longa*	4,912	4,680	22,988	1.12	0.46	1.06	258	106	244
Coconut	*Cocos nucifera*	91,799	1,556.016	142,841	1.8	0.11	1.20	2,571	157	1,714
Groundnut	*Arachis hypogaea*	22,485	1,504	33,817	3.24	0.46	1.69	1096	156	571
Gingelly	*Sesamum indicum*	943	469	442	2.81	0.58	1.91	12	3	8
Sunflower	*Helianthus annuus*	78	1,263	98	2.56	0.35	4.12	3	0.34	4
Cotton	*Gossypium* sp.	7,852	322	2,528	1.86	0.77	0.9	47	20	22
Tobacco	*Nicotiana tabacum*	964	1,496	1,442	5.6	0.53	2.64	81	8	38
Fodder	-	1,374	2,650	3,641	0	0	0	0.00	0.00	0.00
Ragi	*Eleusine corocana*	309	845	261	1.92	0.31	0.47	5	0.81	1
Castor	*Ricinus communis*	226	928	209	0.15	0.26	0.54	0.31	0.55	1
Niger	*Guizottia abyssiniaca*	226	259	58	0.68	0.24	0.46	0.40	0.14	0.27
Banana	*Musa* sp.	7,883	37,086	292,349	1.81	0.42	1.3	5,291	1,228	3,800
Tapioca	*Manihot utilissima*	1,767	14,000	24,738	0.38	0.322	1.1	94	80	272
Onion	*Allium cepa*	3,941	17,654	69,574	3.32	0.54	3.3	2,310	376	2,296
Brinjal	*Solanum melongena*	861	9,153	7,881	2.1	0.32	2.9	165	25	228
Tomato	*Lycopersicon esculentum*	5,534	11,126	61,571	4.8	0.48	3.1	2,955	295	1,908
Bhendi	*Hibiscus esculentus*	699	10,521	7,354	3.3	0.61	2.55	243	45	187
Sugarcane	*Saccharum officinarum*	12,911	45	580,995	0.42	0.18	0.65	2,440	1,046	3,776
Beetroot	*Beta vulgaris*	479	18,000	8,622	0.68	0.12	0.84	59	10	72
Bitter gourd	*Momordica charantia*	535	15,000	8,025	1.16	0.21	1.26	93	17	101
Greens	-	186	7,000	1,302	1.12	0.26	1.3	15	3	17
Radish	*Raphanus sativus*	116	14,000	1,624	0.9	0.11	2.6	15	2	42
Grapes	*Vitis vinifera*	379	32,540	12,333	0.5	0.42	4.6	8	0.96	22
Mango	*Mangifera indica*	3,525	6,443	22,712	1.8	0.186	2.2	408	42	500
Total	-	312,245	-	-	-	-	-	19,892	4,026	16,717

calculated K losses due to leaching in Coimbatore and Erode Districts were 2054 and 1860 t year^{-1}.

N losses (OUT4) calculated using the built-in multiple regression equation in NUTMON-Toolbox for Coimbatore and Erode Districts were 555.17 and 639 t year^{-1}. The estimated soil losses using the universal soil loss equation for these districts were 355 and 383 kg ha^{-1} year^{-1}. The estimated soil loss clearly matched with the soil loss calculated on red and black soils of the study area by Santhanabosu and Sivanappan (1989), who reported losses to the tune of 0.236 to 585 t ha^{-1} year^{-1}.

Quantification of the nutrient balance

Quantification of the nutrient balance of Coimbatore District in western zone of Tamil Nadu revealed that the sum of the input factors (IN1 to IN5) minus output factors (OUT1 to OUT5) produced a negative balance for N (–3160 t year^{-1}) and K (–3073 t year^{-1}) and a positive balance for P (+6423 t year^{-1}) (Surendran and Murugappan 2007b). Similar trend of results was noticed in Erode District; the balances for N and K were negative (−1033 and −17,811 t year^{-1}, respectively), whereas the P

Table 4 Nutrient export through crop residues of Coimbatore District

Crop	Scientific name	Area	Productivity (kg ha^{-1})	Production (t ha^{-1})	Nutrient content (%)			Nutrient removal (t)		
					N	P	K	N	P	K
Paddy	*Oryza sativa*	14,110	5,393	76,088	0.84	0.13	0.78	639	99	593
Sorghum	*Sorghum vulgare*	80,284	477	38,295	0.81	0.28	0.39	310	107	149
Maize	*Zea mays*	17,272	1,688	29,147	0.76	0.13	0.47	222	38	137
Cumbu	*Pennisetum purpureum*	404	3,021	1,220	0.80	0.24	0.58	10	3	7
Pulses	-	30,191	675	20,379	2.01	0.21	1.82	410	43	370
Turmeric	*Curcuma longa*	4,912	7,020	34,482	1.31	0.18	1.02	452	62	352
Coconut	*Cocos nucifera*	91,799	10,125	929,465	0.23	0.04	0.48	2,138	371	4,461
Groundnut	*Arachis hypogaea*	22,485	2,256	50,726	1.23	0.12	1.62	624	61	821
Gingelly	*Sesamum indicum*	943	704	663	1.50	0.41	2.10	10	2	14
Sunflower	*Helianthus annuus*	78	1,895	148	1.81	0.32	4.12	3	0.47	6
Cotton	*Gossypium* sp.	7,852	483	3,793	1.88	0.90	0.90	71	34	34
Tobacco	*Nicotiana tabacum*	964	2,244	2,163	1.68	0.36	2.72	36	8	58
Fodder	-	1,374	3,975	5,462	1.33	0.14	1.38	73	8	75
Ragi	*Eleusine corocana*	309	1,268	392	0.83	0.18	0.47	3	0.70	2
Castor	*Ricinus communis*	226	1,392	315	0.30	0.60	0.54	1	1.89	1.70
Niger	*Guizottia abyssiniaca*	226	389	88	0.48	0.16	0.46	0	0.14	0.40
Banana	*Musa* sp.	7,883	55,629	438,523	1.42	0.18	1.05	6,227	789	4,604
Tapioca	*Manihot utilissima*	1,767	6,500	11,486	1.48	0.21	1.12	170	24	128
Onion	*Allium cepa*	3,941	26,481	104,362	0.88	0.22	1.3	918	229	1,356
Brinjal	*Solanum melongena*	861	13,729.5	11,821	4.2	0.46	4.6	496	54	543
Tomato	*Lycopersicon esculentum*	5,534	16,689	92,357	3.2	0.28	2.8	2,955	258	2,586
Bhendi	*Hibiscus esculentus*	699	15,781.5	11,031	4.1	0.32	1.8	452	35	198
Sugarcane	*Saccharum officinarum*	12,911	5	64,555	0.57	0.16	0.62	368	103	400
Beetroot	*Beta vulgaris*	479	9,000	4,311	0.78	0.12	0.84	34	5	36
Bitter gourd	*Momordica charantia*	535	7,500	4,013	1.16	0.21	1.26	46	8	50
Greens	-	186	0	0	1.12	0.26	1.3	0	0.00	0.00
Radish	*Raphanus sativus*	116	7,500	870	0.9	0.11	2.6	8	0.96	22
Grapes	*Vitis vinifera*	379	7,500	2,843	0.9	0.42	4.6	26	11.94	130
Mango	*Mangifera indica*	3,525	0	-	-	-	-	0	0.00	0.00
Total	-	312,245	-	-	-	-	-	16,702	2,357	17,134
Total removal	-	-	-	-	-	-	-	13,361	1,886	13,707

balance was positive (+4580 t year^{-1}; Table 7). The per hectare N and K balances were also negative for both the districts (−3.3 N and −58.6 N and −10.1 K and −9.8 K kg ha^{-1} year^{-1+}, respectively), whereas P registered a positive balance in cases (+14.5 and + 20.5 kg ha^{-1} year^{-1}, respectively; Fig. 3). The aggregated nutrient balances for the two districts were also negative for N (−4193 t year^{-1}) and K (−20,884 t year^{-1}) and positive for P (+11,003 t year^{-1}; Table 7). The positive balance of P is the result of the accumulation of P over years due to P fertilizer application, and also, the losses were low since the soils in the study area tend to fix P (Kumaraswamy 2001). The positive balance of P will result in an increased risk of nutrient emissions to the environment causing nutrient toxicity. The enhancement of P in soil reserves may lead to the contamination of surface and groundwater causing accelerated eutrophication and poses risks of toxicity to aquatic life. Similarly, for the negative balances of N and K, the reason being the sum of emissions was much higher than the emissions. The negative balances of N and K imply that a net depletion of these nutrients from the soil reserves occurs. N is mobile in the soil system and is also lost from the system by leaching, volatilization of NH_3 in

Table 5 Nutrient export in harvested produces of Erode District

Crop	Scientific name	Area	Productivity (kg ha^{-1})	Production (t ha^{-1})	Nutrient content (%)			Nutrient removal (t)		
					N	P	K	N	P	K
Paddy	*Oryza sativa*	57,485	4,610	265,006	1.16	0.34	0.84	3,073	901	2,226
Sorghum	*Sorghum vulgare*	4,309	922	3,973	1.45	0.55	0.39	58	22	15
Maize	*Zea mays*	4,752	2,288	10,873	1.68	0.41	0.47	183	45	51
Cumbu	*Pennisetum purpureum*	530	845	448	1.92	0.46	0.58	9	2	3
Pulses	-	37,391	550	20,565	3.36	0.37	2.27	691	76	467
Turmeric	*Curcuma longa*	6,964	6,011	41,860	1.44	0.46	1.12	603	193	469
Groundnut	*Arachis hypogaea*	45,142	1,830	82,610	3.72	0.66	1.81	3,072	545	1,495
Gingelly	*Sesamum indicum*	13,663	768	10,493	3	0.61	2.1	315	64	220
Sunflower	*Helianthus annuus*	529	1,750	926	2.4	0.35	4.12	22	3	38
Cotton	*Gossypium* sp.	9,573	390	3,733	1.87	0.77	0.9	70	29	34
Tobacco	*Nicotiana tabacum*	2,820	1,589	4,481	5.6	0.53	2.72	251	24	122
Fodder	-	71,552	0	0	0	0	0	0	0	0
Ragi	*Eleusine corocana*	10,676	845	9,021	1.92	0.31	0.47	173	28	42
Castor	*Ricinus communis*	2,726	928	2,530	0.15	0.26	0.54	4	7	14
Niger	*Guizottia abyssiniaca*	1,582	259	410	0.6	0.12	0.46	2	0	2
Banana	*Musa* sp.	3,757	37,086	139,332	1.84	0.42	1.3	2,564	585	1,811
Tapioca	*Manihot utilissima*	4,906	14,000	68,684	0.35	0.82	1.1	240	563	756
Sugarcane	*Saccharum officinarum*	33,048	45	1,487,160	0.42	0.16	0.65	6,246	2,379	9,667
Onion	*Allium cepa*	2,571	9,913	25,486	3.4	0.58	3.8	867	148	968
Brinjal	*Solanum melongena*	411	7,854	3,228	2.1	0.31	3	68	10	97
Tomato	*Lycopersicon esculentum*	643	9,431	6,064	4.8	0.45	3.2	291	27	194
Bhendi	*Hibiscus esculentus*	411	5,441	2,236	3.3	0.61	3.1	74	14	69
Total	-	315,441	-	-	-	-	-	18,876	5,665	18,760

soils whose pH is more than neutral, and denitrification in soils where submergence is a practice. All the three processes operate in the study area. While comparing the districts, it was found that the high negative K balance in Erode District is mainly due to existing cropping system, in which K-depleting crops like turmeric, tapioca, banana, maize, and paddy are grown. In the case of K, removal of harvested product (OUT1 and OUT2) proved to be the strongest negative contributor, followed by leaching which occurs in the study area since the soil characteristics are conducive for leaching. Yet, the wider negative balance obtained may be due to sub-optimal use of inputs in the study area (Murugappan et al. 1999). Continued nutrient mining process that goes at the expense of soil nutrient from the mineral and organic matter reserves limits the crop yield and renders the land chemically degraded (Murugappan 2000). We can undoubtedly infer that the current practice of cropping system and nutrient management are exhaustive in terms of N and K withdrawals and cause greater drain of these nutrients from soil reserves. This process unchecked might lead to an irreversible loss of soil fertility and eventually jeopardize the production in the years to come and leaving the soils unfertile for the posterity. Declining soil fertility also prevents income generation of the rural community and triggers the migration of the rural population into urban centers in search of income and food at the expense of social security. A nutrient audit model described in this study can effectively play a role in assessing the problems and helps developing strategies and practices that can be used to make useful policy interventions.

Strategy development using a DSS

Nutrient balance at crop and farm levels by NUTMON

Nutrient balances at crop level covering all the FSUs in the farm, which were generated using NUTMON-Toolbox, are presented in Table 8. All the crop activities

Table 6 Nutrient export in crop residues of Erode District

Crop	Scientific name	Area	Productivity (kg ha^{-1})	Production (t ha^{-1})	Nutrient content (%)			Nutrient removal (t)		
					N	P	K	N	P	K
Paddy	*Oryza sativa*	57,485	6,915	397,509	1.18	0.26	1.10	4,691	1,034	4,373
Sorghum	*Sorghum vulgare*	4,309	1,383	5,959	0.88	0.34	0.76	52	20	45
Maize	*Zea mays*	4,752	3,432	16,309	1.19	0.21	1.02	194	34	166
Cumbu	*Pennisetum purpureum*	530	1,268	672	0.84	0.24	0.58	6	2	4
Pulses	-	37,391	585	21,874	2.63	0.27	2.27	575	59	497
Turmeric	*Curcuma longa*	6,964	8,206	57,145	1.51	0.21	1.36	863	120	777
Groundnut	*Arachis hypogaea*	45,142	3,203	144,567	1.46	0.18	1.91	2,111	260	2,761
Gingelly	*Sesamum indicum*	13,663	704	9,612	1.50	0.54	2.10	144	52	202
Sunflower	*Helianthus annuus*	529	2,625	1,389	1.92	0.41	4.12	27	6	57
Cotton	*Gossypium* sp.	9,573	780	7,467	1.87	0.90	0.90	140	67	67
Tobacco	*Nicotiana tabacum*	2,820	2,244	6,328	2.67	0.36	2.72	169	23	172
Fodder	-	71,552	5,300	379,226	1.46	0.38	1.81	5,537	1,441	6,864
Ragi	*Eleusine corocana*	10,676	1,268	13,532	0.83	0.18	0.56	112	24	76
Castor	*Ricinus communis*	2,726	1,392	3,795	0.41	0.60	0.54	16	23	20
Niger	*Guizottia abyssiniaca*	1,582	389	615	0.48	0.16	0.46	3	1	3
Banana	*Musa* sp.	3,757	64,901	243,831	1.98	0.24	1.56	4,828	585	3,804
Tapioca	*Manihot utilissima*	4,906	6,500	31,889	1.92	0.21	1.26	612	67	402
Onion	*Allium cepa*	2,571	17,843.4	45,875	1.46	0.21	1.36	670	96	624
Brinjal	*Solanum melongena*	411	11,781	4,842	4.2	0.45	4.6	203	22	223
Tomato	*Lycopersicon esculentum*	643	14,146.5	9,096	3.8	0.4	3.2	346	36	291
Bhendi	*Hibiscus esculentus*	411	9,521.75	3,913	4.1	0.35	1.9	160	14	74
Sugarcane	*Saccharum officinarum*	33,048	8	264,384	0.78	0.16	0.88	2,062	423	2,327
Total removal	-	315,441	-	-	-	-	-	23,520	4,409	23,829
Farm removal	-	-	-	-	-	-	-	18,816	3,527	19,063

showed a negative balance of N except brinjal, where the N balance (7.4 kg ha^{-1}) was positive. A mixed pattern of positive and negative balances was observed with P. A positive full balance of 16.1 kg P ha^{-1} was noticed with tapioca followed by turmeric (14.1 kg ha^{-1}). P balance was highly negative (−63.8 kg ha^{-1}) with sugarcane. K balance also showed a mixed trend of results. The highest negative K full balance was observed with sugarcane (–204.2 kg ha^{-1}). However, the positive K balance was noticed in sunflower (24.7 kg ha^{-1}). In nutshell, none of the crop activities exhibited a positive balance for all the three nutrients. For the farm as a whole, the nutrient

Table 7 Soil nutrient balance for Western Zone of Tamil Nadu

IN/OUT (t year^{-1})	IN1	IN2	IN3	IN4	IN5	Total	OUT1	OUT2	OUT3	OUT4	OUT5	Total	Balance
1. Soil nutrient balance of Erode District													
N	36,732	6,315	1,132	2,100	0	46,279	18,876	18,816	8,964	556	100	47,312	−1,033
P	11,406	1,790	186	0	473	13,855	5,665	3,527	0	0	83	9,275	4,580
K	13,422	4,330	746	0	3,154	21,652	18,760	19,063	2,054	0	286	40,163	−17,811
2. Soil nutrient balance of Coimbatore District													
N	31,986	4,839	1,058	1,097	0	38,980	19,892	13,361	8,095	693	98.5	42,140	−3,160
P	10,793	1,443	171	0	429	12,836	4,016	1,886	0	0	82.1	5,984	6,423
K	22,715	3,223	692	0	2,860	29,490	16,717	13,707	1,860	0	279	32,563	−3,073

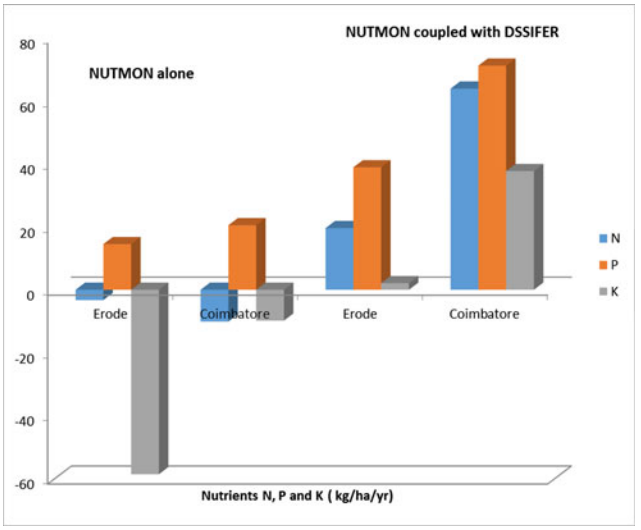

Fig. 3 Soil nutrient balance for Erode and Coimbatore Districts of Tamil Nadu under NUTMON alone and with NUTMON and DSSIFER combinations

balance was expressed as the sum of inputs minus the sum of outputs covering all FSUs, SPUs, and RUs. There has been a slight variation in the nutrient balance of the farm than the individual crops. NUTMON-Toolbox-generated nutrient balance for the experimental farm as a whole showed that the full balances were positive for P and negative for N and K, similar to the trend observed at district level data mentioned earlier (Fig. 3).

Nutrient balance for the farm using NUTMON combined with DSSIFER

The fertilizer recommendation derived from DSSIFER tool for the crops grown at Singampettai irrigated farm were 815.8, 252.5, and 586.4 kg of N, P, and K, respectively (Table 9). The fertilizer prescription for most of the crops revealed that the presently followed state recommendation is sub-optimal and an upward revision is the need of the hour to make the crop production profitable and sustainable. NUTMON-Toolbox-generated nutrient balance was positive for all the three nutrients when the fertilizer program is DSSIFER based. Among the N, P, and K balances, N balances were highly positive at both partial and full balance modes (88.0 and 68.3 kg ha^{-1}, respectively).

Nutrient balance at district level by using NUTMON combined with DSSIFER

Nutrient balances were computed using the NUTMON-Toolbox by replacing the farmer's practice of fertilization with DSSIFER-generated crop and site-specific

Table 8 NUTMON-Toolbox-generated nutrient balance at crop level for the irrigated large farm in Singampettai

Flows Unit	Partial balance (kg ha^{-1}) Nitrogen	Full balance (kg ha^{-1})	Partial balance (kg ha^{-1}) Phosphorus	Full balance (kg ha^{-1})	Partial balance (kg ha^{-1}) Potassium	Full balance (kg ha^{-1})
PPU 1 sugarcane (12,141 m^2)	−140.4	−158.8	−52.9	−52.2	−35.9	−133.8
PPU 2 turmeric (4,047 m^2)	−29.7	−41.3	13.3	14.1	−14.3	−12.6
PPU 3 sugarcane (8,094 m^2)	−190.1	−193.6	−64.4	−63.8	−37.8	−204.2
PPU 4 brinjal (2,023 m^2)	20.8	7.4	−12.4	−11.9	−118.6	−116.7
PPU 5 fallow (2,023 m^2)	0.0	−0.4	0.0	0.5	0.0	2.0
PPU 6 sunflower (8,094 m^2)	−0.7	−5.4	1.0	1.6	22.4	24.7
PPU 7 tapioca (10,117 m^2)	−5.4	−12.7	15.4	16.1	−10.5	−8.2
PPU 8 ratoon cane (8,094 m^2)	−147.4	−150.6	−46.6	−46.0	−124.1	−153.3
PPU 9 tapioca (4,047 m^2)	−40.0	−43.5	10.9	11.6	−7.7	−5.7

Table 9 NUTMON-Toolbox-generated nutrient balance when fertilizer program is from DSSIFER for the experimental farms in Singampettai

Flows	Inputs (kg)				Outputs (kg)				Partial balance (kg)	Full balance (kg)	Partial balance (kg ha^{-1})	Full balance (kg ha^{-1})
Nutrient	IN1	IN2	IN3	IN4	OUT1	OUT2	OUT3	OUT4				
Nitrogen	815.8	3.9	23.1	0.0	170.5	135.2	133.2	4.8	514.0	399.1	88.0	68.3
Phosphorus	252.5	0.9	3.8	0.0	44.9	18.3	0.0	0.0	190.2	194	32.6	33.2
Potassium	586.4	1.2	15.2	0.0	104.7	265.7	4.8	0.0	217.2	227.6	37.2	39.0

fertilizer recommendations and the farmer's crop yield with the yield targets fixed in DSSIFER. The results revealed that the nutrient balances were positive at both farm and district levels. The mean N, P, and K balances were 19.6, 38.7, and 2.1 kg ha^{-1} year^{-1} for Erode District and 63.9, 71.2, and 37.7 kg ha^{-1} year^{-1} at district level (Fig. 3). Thus, fertilizer program generated by DSSIFER is not only balanced but also ensures sustainability of the agro-production systems.

Other management options for mitigation of nutrient mining

The major negative contributor is the outflow through harvested crop produce, which cannot be curtailed since the main aim of the farmers and policy makers is to enhance the productivity to feed the enormous population. Solutions to nutrient depletion and accumulation need to focus on economically feasible and socially acceptable technologies. There is a wide range of management interventions (nutrient-saving technologies, viz., increasing the use efficiency and preventing/minimizing the losses) to influence soil nutrient balances.

Some of the strategies are discussed below, which are relevant to the study area.

1. Split applications of fertilizers can be made to match the nutrient requirement of the crop with that of the nutrient availability in soil, thereby increasing the efficiency of applied fertilizers.
2. The farmers in the study area have to be trained for efficient recycling of farm wastes, proper manure collection, and storage methods so as to achieve a positive balance.
3. Farmers should be trained in such a way to know about the whole system of their farm, nutrient inflows and outflows creating awareness about the activities which deplete their soil fertility, and also training on efficient management techniques to mitigate them (Murugappan 2000).
4. Crop rotation should involve shallow-rooted crop and deep-rooted crop for efficient transfer of nutrient flow from sub-soil to surface soil (Hartemink 1994).
5. Introduction of green manures and legumes in the system is one of the technological options to replenish the soil nitrogen level without any external inputs.
6. Even though farmers are mainly concerned with the current season, awareness has to be created about the effects of soil fertility decline. Feedback mechanism has to be developed or included in the training program so that everyone will know about declining soil fertility, which in turn reduce the yield in a long run.
7. Nutrient-depleting and nutrient-accumulating crops should be in the cropping system, thereby making the system able for recuperating the fertility level.
8. Adoption of precision agriculture, site-specific nutrient management, and drip fertigation will help to improve/sustain the soil fertility level (Jayakumar et al. 2014; 2015).
9. Practice of integrated nutrient management comprising integrated usage of chemical fertilizers and other source of organic manures such as biofertilizers will result in sustainable crop yields without any detrimental effect on agro-ecological balance (Surendran and Vani 2013; Surendran et al. 2016).

Conclusions

The calculated nutrient balances for Coimbatore and Erode Districts in a semi-arid region of South India, using NUTMON methodology, were negative for nitrogen (N −3.3 and −10.1 kg ha^{-1}) and potassium (K −58.6 and −9.8 kg ha^{-1}) and positive for phosphorus (P +14.5 and 20.5 kg ha^{-1}). Soil nutrient pool has to offset the negative balance of N and K; there will be an expected mining of nutrient from the soil reserve in the study area. DSSIFER-based fertilizer recommendation turns the negative balances of N and K in to a positive one at crop, farm, and district levels. These DSSs, viz., NUTMON and DSSIFER, serve as a tool to identify the depletion of nutrients and help to suggest the management options using a systematic approach. The management options to mitigate nutrient mining with an integrated system approach are also discussed. However, it is concluded that one single technology does not solve these nutrient-related problems and solutions have to be sought in a suite of technologies through integrated nutrient management (INM)/best management practices (BMPs).

Acknowledgments The authors wish to thank Indian Council of Agricultural Research for funding this study. Besides, the authors wish to thank E.M.A. Smaling, Andre De Jager, and Jetse Stoorvogel for providing the NUTMON-Toolbox, relevant literatures, and also for the suggestions during the course of the study. We would like to immensely thank the anonymous reviewers for their valuable comments and suggestions made for refining the manuscript.

References

Abedin, M. J., Blume, H. P., Bhuiya, Z., & Eaquab, M. (1991). Water and nutrient dynamics of paddy soil of Bangladesh. *Pfl-Ern Bodenk., 154*, 93–99.

Agnihotri, Y., Sud, A. D., Mittal, S. P., & Bansal, R. C. (1987). A note on estimation of crop management factor of the universal soil loss equation at Chandigarh. *Indian Journal of Soil Conservation, 15*(2), 44.

Askegaard, M., & Eriksen, J. (2000). Potassium retention and leaching in an organic crop rotation on loamy sand as affected by contrasting potassium budgets. *Soil Use and Management, 16*, 200–205.

Bassanino, M., Dario, S., Laura, Z., & Carlo, G. (2011). Nutrient balance as a sustainability indicator of different agro-environments in Italy. *Ecological Indicators, 11*, 715–723.

Bekunda, M., & Manzi, G. (2003). Use of the partial nutrient budget as an indicator of nutrient depletion in the highlands of southwestern Uganda. *Nutrient Cycling and Agroecosystems, 100*, 1–10.

Biswas, T. D., & Mukherjee, K. (1982). *Textbook of soil science*. New Delhi: Tata McGraw Hill Publishers.

Bjornberg, D. L., Kanwar, R. S., & Melvin, S. W. (1996). Seasonal changes in flow and nitrate loss from subsurface drains as affected by tillage. *Transactions of the ASAE, 39*(3), 961–976.

Bremner, J. M., & Keeney, D. R. (1985). Determination and isotope–ratio analysis of different forms of nitrogen in soils: 3. Exchangeable ammonium, nitrate and nitrite by extraction-distillation methods. *Soil Science Society of America Proceedings, 30*, 577–582.

Carolien Kroeze Aerts, R., Van Breemen, N., Van Dam, D., Van der hoek, K., Hoosbeek, M., Kros, H., Van oene, H., Oenema, O., Albert, T., Van der Veeren, R., & De Vries, W. (2003). Uncertainties in the fate of nitrogen I: an overview of sources of uncertainty illustrated with a Dutch case study. *Nutrient Cycling and Agroecosystems, 66*, 43–69.

Chhonkar, P. K. (2003). Organic farming: science and belief. *Indian Society of Soil Science, 51*(4), 365–377.

Cobo, J. G., Dercon, G., & Cadisch, G. (2010). Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. *Agriculture, Ecosystems and Environment, 136*, 1–15.

Dang, M. V. (2005). Soil-plant nutrient balance of tea crops in the northern mountainous region, Vietnam. *Agriculture, Ecosystems and Environment, 105*, 413–418.

De Jager, A., Onduru, D., Van Wijk, M. S., Vlaming, J., & Gachimbi, G. N. (2001). Assessing sustainability of low external input farm management systems with the nutrient monitoring approach; a case study in Kenya. *Agricultural Systems, 69*, 99–118.

De Ridder, N., Breman, H., Van Keulen, H., & Stomph, T. J. (2004). Revisiting a 'cure against land hunger': soil fertility management and farming systems dynamics in the West African Sahel. *Agricultural Systems, 80*, 109–131.

De vries, W.A., Leip, D.J., Reinds, J., Kros, J.P., Lesschen., & Bouwman, A.F. (2011). Comparison of land nitrogen budgets for European agriculture by various modeling approaches. *Environment Pollution*, 1-15. doi:10.1016/j.envpol.2011.03.038.

Derwent, R. G., Dollard, G. J., & Metcalfe, S. E. (1988). On the nitrogen budgets for United Kingdom and West Europe. *Quarterly Journal of Royal Meteorological Society, 114*, 1127–1152.

Dobermann, A., Sta Cruz, P. C., & Cassman, K. G. (1996). Fertilizer inputs, nutrient balance and soil nutrient supplying power in intensive irrigated rice systems. I Potassium uptake and K balance. *Nutrient Cycling and Agroecosystems, 46*, 11–21.

Duong, T. T., Le, T. P. Q., Dao, T. S., Pflugmacher, S., Rochelle-Newall, E., Hoang, T. K., Vu, T. N., Ho, T. C., & Dang, D. K. (2012). *Seasonal variation of cyanobacteria and microcystins in the Nui Coc reservoir. Journal of Applied Phycology:* Northern Vietnam. doi:10.1007/s10811-012-9919-9.

Erisman, J. W., Galloway, J. N., Seitzinger, S., Bleeker, A., Dise, N. B., Petrescu, A. M., Leach, A. M., & de Vries, W. (2013). Consequences of human modification of the global nitrogen cycle. *Philosophical Transactions of the Royal Society, 368*, 0116. doi:10.1098/rstb.2013.0116.

Faerge, J., & Magid, J. (2004). Evaluating NUTMON nutrient balancing in Sub-Saharan Africa. *Nutrient Cycling and Agroecosystems, 69*, 101–110.

FAI. (2010). *Fertilizer statistics published by The Fertilizer Association of India*. New Delhi.

FAO. (2003). *Assessment of soil nutrient balance* (Approaches and methodologies. FAO Fertilizer and Plant Nutrition Bulletin 14). Rome: FAO.

FAO. (2004). *Scaling soil nutrient balances. Enabling mesolevel applications for African realities. FAO Fertilizer and Plant Nutrition Bulletin 15*. Rome: FAO.

Fethi, S., & Leip, A. (2015). Estimating the gross nitrogen budget under soil nitrogen stock changes: a case study for Turkey. *Agriculture, Ecosystems and Environment, 205*, 48–56.

Fowler, D., Coyle, M., Skiba, U., Sutton, M. A., Cape, J. N., Reis, S., Sheppard, L. J., Jenkins, A., Grizzetti, B., Galloway, J. N., Vitousek, P., Leach, A., Bouwman, A. F., Butterbach-Bahl, K., Dentener, F., Stevenson, D., Amann, M., & Voss, M. (2013). The global nitrogen cycle in the twenty-first century. Philosophical Transactions of the Royal Society. *B. Biological Science, 368*, 0130164. doi:10.1098/rstb.2013.0164.

Handa, B. K. (1998). Content of potassium in ground water in India. *Fertilizer News, 33*(11), 15–27.

Hartemink, A. E. (1994). *Inorganic nitrogen dynamics under different land use systems on an oxisol in western Kenya*. M.Sc: Thesis Wageningen Agricultural University, The Netherlands.

IFPRI. (1995). *A 2020 vision for food, agriculture and the environment. IFPRI* (p. 56). Washington DC: International Food Policy Research Institute and Food and Agriculture Organization of the United Nations.

IISD (2009). Linking farm-level measurement systems to environmental sustainability outcomes: challenges and ways forward. Published by the International Institute for Sustainable Development, Canada.ISBN:81-85460-40-X.

Jayakumar, M., Surendran, U., & Manickasundaram, P. (2014). Drip fertigation effects on yield, nutrient uptake and soil fertility of Bt Cotton in semi arid tropics. *International Journal of Plant Production, 8*, 375–390.

Jayakumar, M., Surendran, U., & Manickasundaram, P. (2015). Drip fertigation program on growth, crop productivity, water, and fertilizer use efficiency of Bt Cotton in semi-arid tropical region of India. *Communications in Soil Science and Plant Analysis, 46*(3), 293–304.

Katyal, J. C. (2001). Fertilizer use situation in India. *Journal of Indian Society of Soil Science, 49*, 570–592.

Khai, N. M., Ha, P. Q., & Oborn, I. (2007). Nutrient flows in small-scale peri-urban vegetable farming systems in Southeast Asia—a case study in Hanoi. *Agriculture, Ecosystems and Environment, 122*, 192–202.

Krishna Prasad, V., Badarinath, K. V. S., Yonemura, S., & Tsuruta, H. (2004). Regional inventory of soil surface nitrogen balances in Indian agriculture (2000–2001). *Journal of Environmental Management, 73*, 209–218.

Kumar, V., Anil, R., Narwal, S. P., & Kuhad, M. S. (2001). Nutrient mining in agro climatic zones of Haryana. *Fertilizer News, 46*(4), 81–92.

Kumaraswamy, S. (2001). Organic farming principles and practices. *Kisanworld, Chennai, 28*(3), 15–16.

Lam, N. T., Patanothai, A., Limpinuntana, V., & Vityakon, P. (2005). Land use sustainability of composite swiddening in the uplands of Northern Vietnam: nutrient balances of swidden fields during the cropping period and changes of soil nutrients over the swidden cycle. *International Journal of Agriculture Sustainability, 3*, 57–68.

Leip, A., Wolfgang Britz Franz Weiss., & Wim de Vries (2011). Farm, land and soil nitrogen budgets for agriculture in Europe calculated with CAPRI. *Environmental Pollution, 159*(11), 3243–3253.

Lesschen, J. P., Stoorvogel, J., Smaling, E. M. A., Heuvelink, G. B. M., & Veldkamp, A. (2007). A spatially explicit methodology to quantify soil nutrient balances and their uncertainties at national level. *Nutrient Cycling and Agroecosystems, 78*, 111–131.

Merck Vet Manual, (1998). In The Merck Veterinary Manual (Eds) Susan E. Aiello. www.Merckvetmanual.com.

Mitchell, J. K., & Brubenzer, G. D. (1980). Soil loss estimation. In M. J. Kirkby, R. P. C. Morgan, et al. (Eds.), *Soil erosion* (pp. 17–62). London: John Wiley & Sons.

MoA. (2013). *Agricultural statistics at a glance*. Government of India. Available online at http://dacnet.nic.in/eands/.html.

Murugappan, V. (2000). *Integrated nutrient management—the concept and overview*. In: Theme papers on Integrated nutrient management–A joint publication of Tamil Nadu Agricultural University and Tamil Nadu Department of Agriculture.

Murugappan, V., Santhy, P., Selvi, D., Muthuvel, P., & Dakshinamoorthy, M. (1999). Land degradation due to potassium mining under high intensive cropping in semiarid tropics. *Fertilizer News, 44*, 75–77.

NBSSLUP .(1997). Soils of Tamil Nadu for optimising land use, NBSS Publ.46b, 1997

OECD. (2010). *Workshop on agri-environmental indicators: lessons learned and future directions*. www.oecd.org/agriculture/env/indicators/workshop.

Omoti, U., Ataga, D. O., & Isenmila, A. E. (1983). Leaching losses of nutrients in oil palm plantations determined by tension lysimeters. *Plant and Soil, 73*, 365–376.

Paul, E.A. (1988). Towards the year 2000. Directions for future nitrogen research. *In* Wilson, J.R.(eds.) Advances in nitrogen cycling in agricultural ecosystems pp. 417-425.

Phong, L. T., Stoorvogel, J. J., van Mensvoort, M. F., & Udo, H. M. J. (2011). Modeling the soil nutrient balance of integrated agriculture-aquaculture systems in the Mekong Delta, Vietnam. *Nutrient Cycling and Agroecosystems, 90*, 33–49.

Pratap, N., Verma, B., & Rao, C. (1978). *Prediction of rainfall erosion index potential and some parameters of USLE* (pp. 12–13). In: National symposium on soil conservation and water management at Dehradun.

Redding, M. (1999). *Survey of potential of manure for meeting crop nutrient needs with integrated nutrient management in Madhya Pradesh, India*. Available online at www.dpi.qld.gov.au/environment/1915.html.

Santhanabosu, S., & Sivanappan, R. K. (1989). Runoff and soil loss on red and black soils of Coimbatore District. *Indian Journal of Soil Conservation, 17*(2), 49–54.

Sapek, A., & Sapek, B. (1993). Assumed non-point pollution based on the nitrogen budget in polish agriculture. *Water Science and Technology, 28*, 483–485.

Schlecht, E., & Hiernaux, P. (2004). Beyond adding up inputs and outputs: process assessment and upscaling in modelling nutrient flows. *Nutrient Cycling and Agroecosystems, 70*, 303–319.

Season and crop reports (2010). Department of Agriculture, Govt. of Tamil Nadu, Chennai, Tamil Nadu, India.

Sheldrick, W. F., Keith Syers, J., & Lingard, J. (2003). Soil nutrient audits for China to estimate nutrient balances and output/input relationships. *Agriculture, Ecosystems and Environment, 94*, 341–354.

Smaling, E.M.A., (1998). Nutrient balances as indicators of productivity and sustainability in Sub-Saharan African agriculture. Agriculture, Ecosystems and Environment, 71/1, 2, 3 (Special issue), p 283.

Smaling, E. M. A., & Fresco, L. O. (1993). A decision support model for monitoring nutrient balance under agricultural land use (NUTMON). *Geoderma, 60*, 235–256.

Smaling, E. M. A., Stoorvogel, J. J., & Windmeijer, P. N. (1993). Calculating soil nutrient balance in Africa at different scales. II District scale. *Fertilizer Research, 35*, 237–250.

Smil, V. (2011). Nitrogen cycle and world food production. *World Agriculture, 2*, 9–13.

Soil Atlas. (1998). *Soil survey and land use organization*. Coimbatore, India: Department of Agriculture, Government of Tamil Nadu.

Stoorvogel, J. J., & Smaling, E. M. A. (1990). *Assessment of soil nutrient depletion in Sub-Saharan Africa, 1983–2000 report 28*. Soil and Water Research (SC-DLO), Wageningen: The Winand Staring Centre for Integrated Land.

Stoorvogel, J. J., & Smaling, E. M. A. (1998). Research on soil fertility decline in the tropical environments. Integration of spatial scales. *Nutrient Cycling and Agroecosystems, 50*, 151–158.

Stoorvogel, J. J., Smaling, E. M. A., & Janssen, B. H. (1993). Calculating soil nutrient balance in Africa at different scales. I Supranational scale. *Fertilizer Research, 35*, 227–235.

Surendran, U., & Murugappan, V. (2007a). A micro and meso level modeling study for assessing sustainability in semi arid tropical agro ecosystem using NUTMON–Toolbox. *Journal of Sustainable Agriculture, 29*(2), 151–179.

Surendran, U., & Murugappan, V. (2007b). Nutrient budgeting in tropical agro ecosystem-modeling district scale soil nutrient balance in Western Zone of Tamil Nadu using NUTMO-Toolbox. *International Journal of Soil Sciences, 2*(3), 159–170.

Surendran, U., & Murugappan, V. (2010). Pragmatic approaches to manage soil fertility in sustainable agriculture. *Journal of Agronomy, 9*(1), 57–69.

Surendran, U., & Vani, D. (2013). Influence of arbuscular mycorrhizal fungi in sugarcane productivity under semiarid tropical agro ecosystem in India. *International Journal of Plant Production, 7*(2), 269–278.

Surendran, U., Ramesh, V., Jayakumar, M., Marimuthu, S., & Sridevi, G. (2016). Improved sugarcane productivity with tillage and trash management practices in semi arid tropical agro ecosystem in India. *Soil & Tillage Research, 158*, 10–21. doi:10.1016/j.still.2015.10.009.

Sutton, M. A., Bleeker, A., Howard, C. M., Bekunda, M., Grizzetti, B., de Vries, W., Van Grinsven, H. J. M., Abrol, Y. P., Adhya, T. K., Billen, G., Davidson, E., Datta, A., Diaz, R., Erisman, J. W., Liu, X. J., Oenema, O., Palm, C., Raghuram, N., Reis, S., Scholz, R. W., Sims, T., Westhoek, H., & Zhang, F. S. (2013). *Centre for Ecology and Hydrology*. Edinburgh on behalf of the Global Partnership on Nutrient Management and the: International Nitrogen Initiative. Our nutrient world: the challenge to produce more food and energy with less pollution, Retrieved from: http://www.initrogen.org/sites/default/files/documents/files/ONW.pdf.

Tandon, H. L. S. (1992). *Fertilizers, organic manures, recyclable wastes and biofertilizers*. Fert. Dev: Corporation, New Delhi.

Tandon, H. L. S. (1997). Organic resources: an assessment of potential supplies, their contribution to agricultural productivity and policy issues for Indian Agriculture from 2000-2025. In J. S. Kanwar & J. C. Katyal (Eds.), *Plant nutrient needs, supply efficiency and policy issues: 2000-2025*. New Delhi: National Academy of Agricultural Sciences.

Tisdale, S.L., Nelson, W.L., & Beaton, J.D. (1985). Soil fertility and fertilizers (4th ed.) Macmillan Publishing Company, New York, USA.

Van Noordwijk, M. (1999). Nutrient cycling in ecosystem versus nutrient budgets of agricultural systems. In E. M. A. Smaling, O. Onema, & L. O. Fresco (Eds.), *Nutrient disequilibria in agro ecosystems: concepts and case studies* (pp. 1–25). Wallingford: CAB International.

Vlaming, J., van den Bosch, H., van Wijk, M. S., de Jager, A., Bannink, A., & van Keulen, H. (2001). *Monitoring nutrient flows and economic performance in tropical farming systems (NUTMON)*. Green World Research and Agricultural Economics Research Institute, LEI, The Netherlands: Alterra.

Wenner, C. G. (1981). Soil conservation in Kenya. Ministry of Agriculture, Soil conservation unit, Nairobi.

Wijnhoud, J. D. (2007). *Nutrient budgets, soil fertility management and livelihood analyses in Northeast Thailand: a basis for integrated rural development strategies in developing countries*. Dissertation: Wageningen University, Wageningen, The Netherlands.

Wischmeier, W.H. and Smith, D.D. 1978. Predicting rainfall erosion losses from crop land east of the rocky mountains. *Agric Hand Book No.282*. ARS, USDA, Agriculture Hand book No. 537 , Washington DC.

World Bank. (2007). *World bank development report (2008): agriculture for development*. Washington, D.C.: World Bank.

Yadav, R. L., Dwivedi, B. S., Singh, V. K., & Shukla, A. K. (2001). Nutrient mining and apparent balances in different agroclimatic zones of Uttar Pradesh. *Fertilizer News, 46*(4), 13–18.