Soil Survey, Classification and Mapping in Sri Lanka: Past, Present and Future

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Abstract

Soil information is indispensable for sustainable use of the soil resource. Since its initiation in 1887, soil survey, classification and mapping activities in Sri Lanka have progressed through three successive stages. The latest soil maps of Sri Lanka developed through Sri Lanka-Canada soil resource project (1999–2004) are available at scales of 1:250,000–1:500,000. These choropleth soil maps delineate mapping units at soil series level, but due to the coarse nature of the mapping scale, majority of mapping units are either associations or complexes. These maps and the databases have primarily served for agricultural planning and management at its best. The state-of-the-art digital soil mapping techniques have been used in Sri Lanka mostly to generate soil information required for small-scale studies indicating a consistent development of expertise on advances in soil mapping. Presently, the need of soil information has expanded beyond its classical uses and has become a prerequisite for addressing environmental issues and food, energy and water security. These requirements are driving new demands for better soil maps at finer resolution. Catering the present soil information demand, the next national soil survey needs to be performed at a scale of 1:25,000 or larger using soil properties-based map legend. The multidisciplinary nature of the usage of soil information requires a collective decision of scientists on the soil properties to be considered for future mapping activities. Ultimately, the development of web-based national spatial soil information systems is a viable option to publish the next-generation digital soil information of Sri Lanka.

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4.1   Introduction

Sri Lanka consists of 64,454 km^2 of land area with a population of 21.7 million as of 2018. Further, about 1156 km^2 covers inland water bodies. When unsuitable terrain and wildlife reservations are added, about 35,000 km^2 of land become not arable. Therefore, the per capita arable land becomes as low as 0.14 ha indicating heavy pressure on land resource. Most of the rural people make a living from land-based activities and the per capita land area will further reduce with land degradation and increase in population. Therefore, there is a need to survey, classify and map the soils of Sri Lanka for sustainable management to ensure food security for future generations.

4.2   Diversity of Soils of Sri Lanka

The soil is a product of nature and it takes about 3000 years to form a 2.5 cm layer of soil under natural conditions. Soil is formed from parent material due to climate, topography, vegetation and organisms acting on the parent material. More than 90% of the rocks in Sri Lanka which weathers to form parent material are made up of pre-Cambrian rocks, while the rest is mainly sedimentary rocks towards the north-western and northern parts of the country. The variations of different rock types from Vijayan to Highland Complex and to Wanni Complex and then to more recent Miocene deposits are shown in Fig. 4.1. These different complexes are made out of different rock types which give rise to different parent materials resulting in different soils, and more details could be found elsewhere (Indraratne 2010; Panabokke 1996).

The climate of Sri Lanka shows a very high variability. Rainfall, the major climatic factor of soil formation, varies from 830 mm in the driest areas to 5750 mm in the wettest areas of the country. The rainfall zones (wet, intermediate and dry zone) with a combination of the elevation zones (low, mid and up country), which are related to variability of ambient temperature, give rise to the seven main agroclimatic zones. By considering many other factors, these zones are further divided to 46 agroecological regions (Punyawardena 2008) showing the ecological diversity. Topography, the next factor in soil formation, contributes to variation of soils in short range. The flat topography in the coastal area (0–2% slope) becomes undulating (2–8%), to rolling (8–16%) and subsequently to hilly (16–32%) when moving to the central highlands of the country.

The differences in the topography with the rise and fall of the water table create well-drained, imperfectly drained and poorly drained areas forming different soils along the centenary landscape with the same agroecological region and similar
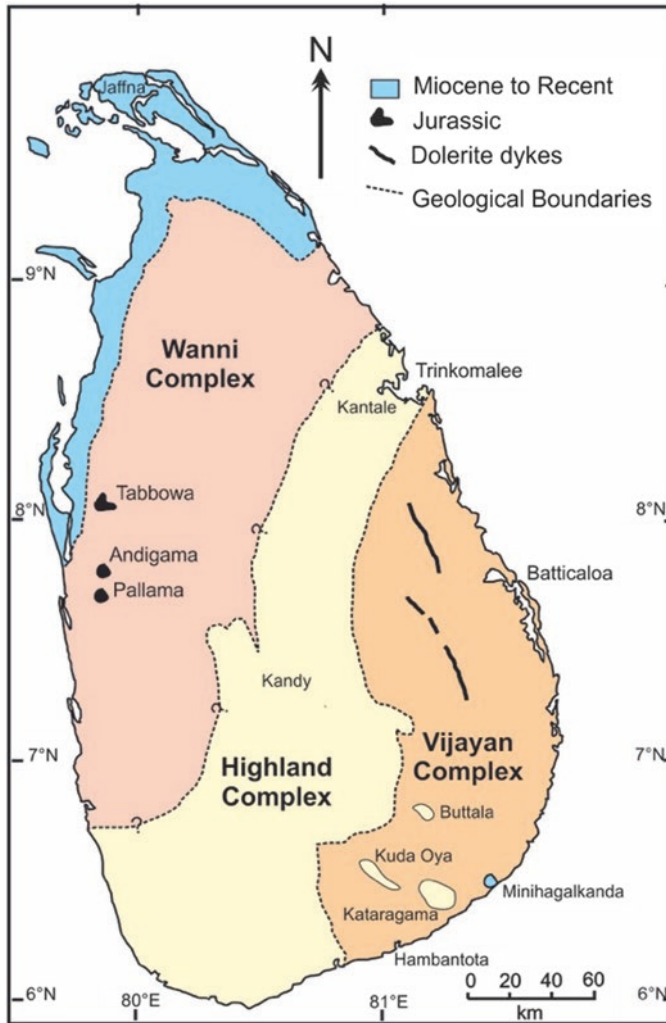
Fig. 4.1 Simplified geological map of Sri Lanka (modified after Cooray 1994)

parent materials. With the variation in soil-forming factors of parent material, climate and topography, Sri Lanka is very rich in soil diversity where more than 102 soil series have been identified by the Soil Science Society of Sri Lanka (Mapa 2014). This soil diversity shows the need for surveying, classifying and mapping the soil resource for sustainable management.

4.3   Soil Survey and Mapping in Sri Lanka Using Traditional Soil Survey Techniques

The need of systematic soil information inventories aroused as the perception and understanding of mankind on the non-renewable nature of soil resource and its crucial role in deciding their existence. The "Great Dust Bowl" of the 1930s in the United States of America was a triggering factor for many nations including Sri Lanka to initiate systematic soil surveys and production of maps to support the sustainable use of soil resource. Soil survey and mapping history of Sri Lanka could be divided into three distinct periods as the Pre-independence Era (before 1948), Post-independence Era (from 1948 to 1972) and the Present Era (from 1972 to today). All these mapping endeavours were relied on traditional mental pedologic models developed by soil mappers (Hudson 1992). These empirical or conceptual models qualitatively relate soil properties measured at a limited number of sites with landscape and environmental variables. The soil variability is presented as by dividing the survey area into polygons called individual delineations of map units. A map unit contains one or more soil types identified according to a chosen soil classification method.

The concept of zonal, azonal and intrazonal soils was the consideration in the early classification of soils of Sri Lanka and gradually shifted to great soil groups-based local classification and then to USDA soil taxonomy and FAO-WRB legend. The accompanying soil survey report with the soil map describes the soil types enclosed in mapping units. Among these mapping attempts, the most comprehensive survey report consisting of the description of 102 soil series with soil horizons-based analytical data was produced at the soil survey conducted during the period 1999–2007 under the SRICANSOL project. Burrough (1993) described two models representing spatial variability of soils, namely, discrete and continuous models (Fig. 4.2). The continuous model resembles the natural spatial variability of soil. The discrete model is a generalization of the continuous model depicting abrupt changes of soil properties at boundaries but uniform soil between boundaries. This model has been used in soil mapping endeavours conducted in Sri Lanka which resulted in area-class or choropleth soil maps.

4.3.1   Pre-independence Era of Soil Survey (Before 1948)

The earliest documented evidence on the soils of Sri Lanka (then Ceylon) could be traced to the publication by Hughes (1887) on "Ceylon Coffee Soils and Manures" during the time coffee was introduced to the country as a plantation crop by the British government. Once the coffee plantations were destroyed by the coffee rust disease, tea was introduced. The nutrient status and physical constituents of tea-grown soils were studied by Bamber (1900). Subsequently, Harbord (1913) studied the coconut-grown soils, and Bruce (1922) studied rice and forest soils in the country. Similar to many other countries, soils of Sri Lanka were then classified
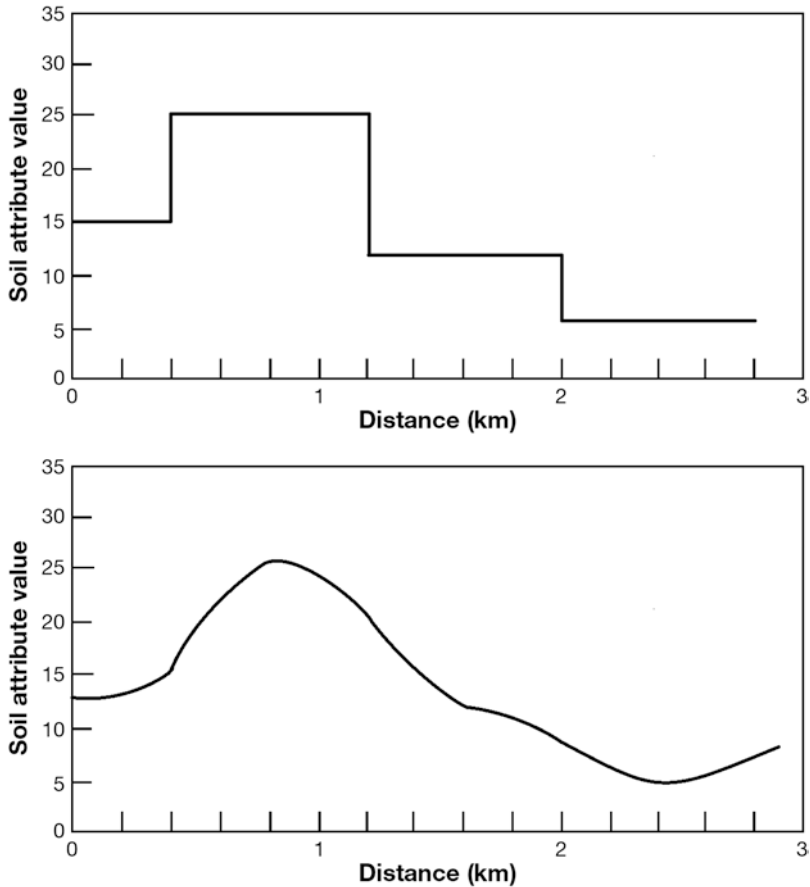
Fig. 4.2 Models for representing the spatial variation of soil properties, (top) discrete model and (bottom) continuous model (after Burrough 1993)

according to the crops grown as cinnamon soils, tea soils, rice soils, etc. Eden (1929) recognized the importance of the soil profile as the unit of study and attempted to classify the tea-grown soils and established the first factorial experiment at the St. Coombs Estate of the Tea Research Institute at Talawakelle.

The most prominent contribution to Soil Survey and Classification during this era was by Dr. A.W.R. Joachim who published 13 articles on "Studies of Ceylon soils" from 1935 to 1940 with his co-workers, S. Kandiah and D.G. Panditesekere (Joachim 1935a, b, 1937, 1955; Joachim and Kandiah 1935a, b, 1937, 1938, 1939, 1940; Joachim and Panditesekere 1935, 1937, 1938). In these, they explained adoption of modern methods for soil studies, classification of soils and their application to Sri Lankan (then Ceylon) soils. They described the typical soil groups of Sri Lanka consisting of red and yellow earths to forest soils of the wet and dry
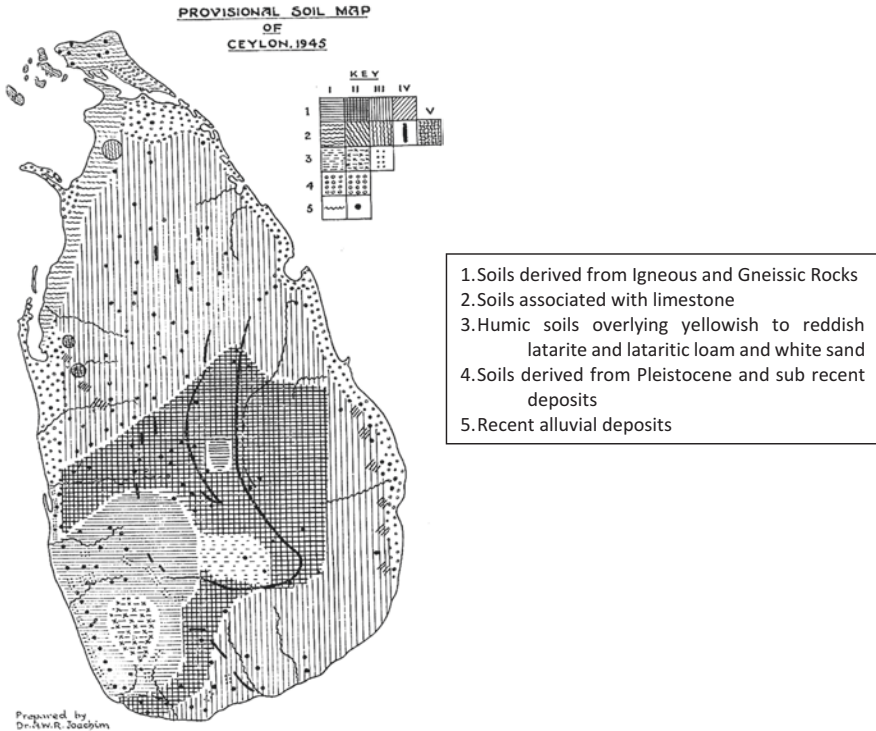
Fig. 4.3 The first provisional soil map of Sri Lanka (adopted from Joachim 1945—refer Table 4.1 for the description of the legend)

zones, wet and dry Patna soils, light sandy soils of the dry zone and soils associated with limestone in Jaffna Peninsula derived from Miocene limestone deposits. The soils of the Matale and Nalanda areas were named as red loams and chocolate red heavy loams overlying crystalline limestone, mainly dolomite.

To collect information related to pedology, they included two important aspects of modern soil concepts: the "unit of soil studies" to be the soil profile and the importance of characterizing the clay complex. Using these information, the first provisional soil map of Sri Lanka was published by Joachim and his co-workers in 1945 (Joachim 1945) which is shown in Fig. 4.3. They considered the soil-forming factors which are the nature of parent rock, climate, vegetation and topography in developing this soil map.

In his scholarly work, Joachim (1945) identified the incompleteness of the zonality-based classification to classify the diverse range of soils of Sri Lanka; thus, he included two additional categories (categories 3 and 4) in addition to zonal (category 1), intrazonal (category 2) and azonal (category 5) soils (Table 4.1).

Table 4.1 Soil classification used by Joachim (1945)

Categories	Units
1. Soils derived from igneous and gneissic rocks	1. Lateritic (cabook) and lateritic reddish yellow loams and gravelly loams of ultra-wet zone 2. Reddish to yellowish red lateritic loams of wet zone 3. Lateritic and non-lateritic red, reddish brown and dark grey loams of dry zone 4. Non-lateritic grey brown sandy loams
2. Soils associated with limestone	1. Red loams derived from Miocene limestone 2. Grey loams derived from Miocene limestone 3. Black heavy loams associated with Miocene and crystalline limestone 4. Brown red loams associated with crystalline limestone (mainly dolomite) 5. Red loams associated with Jurassic limestone
3. Humic soils overlying yellowish to reddish laterite and lateritic loams and white sands	1. Grassland *(Patna)* soils (wet and dry) 2. Fernland *(Kekilla)* soils 3. Low-lying peaty soils (paddy lands, etc.)
4. Soils derived from Pleistocene and sub-recent deposits	1. Red and brown sandy soils (coconut soils) over gravel 2. White sands (cinnamon soils, etc.)
5. Recent alluvial deposits	1. Reddish brown, grey brown and yellowish brown loams and clays 2. Existing paddy (gley) soils

4.3.2   Post-independence Era of Soil Survey (from 1948 to 1972)

During the beginning of this period, the government policy on agriculture gradually shifted to dry zone due to the initiation of irrigation development schemes. A methodological study on soil mineralogy was conducted by Panabokke (1956), which was helpful in future soil classification studies. Rice soils and the topo-sequence of the Hewagama and Hapitigama Korale were studied by Thenabadu and Fernando (1966) and Thenabadu et al. (1966). Subsequently, in collaboration with a Japanese soil scientist, a soil survey was conducted in four selected rice-grown areas, and a classification was proposed according to the differences in hydro-morphism as observed by gleying and mottling of submerged soils (Tokutome et al. 1971).

Much needed aerial photographs for soil survey work became available in 1963–1968 with the Hunting Survey Corporation of Canada, conducting resource surveys of 15 river basins in the north-western part of the country and in Kirindi Oya basins of the south of Sri Lanka. This provided the much-needed landscape and soil information (Hunting Survey Corporation 1963; Hunting Survey Corporation 1968) for future soil surveys. Using these information, and based on morphological characters, Mooman and Panabokke (1961) classified the soils of the country into 14 great soil groups. The great soil group (GSG) was defined as a soil unit with the same arrangement of genetic horizons in the soil profile immaterial of their thickness.

An important landmark during this time was the formation of the Soil Science Society of Sri Lanka (SSSSL) in 1969 whereby soil scientists in government departments such as agriculture and irrigation joined with the scientists from the plantation research institutes and private sector for the development of soil science. The mandate of the society was to promote the advancement of soil science in the country, to foster relationships among soil scientists and to disseminate the knowledge pertaining to soil science by publishing a journal and by other means. From then, most of the soil survey and classification work took a team approach through the leadership of the SSSSL.

Combining the data collected by Land and Water Use Division of the Department of Irrigation for the Mahaweli Project, the soil classification proposed by Moorman and Panabokke (1961) was revised by De Alwis and Panabokke (1972). This was done by extending the 14 great soil groups to 23 and proposing equivalent soil taxonomic names according to Seventh Approximation of USDA soil taxonomy, which was the international soil classification method used at that time (Soil Survey Staff 1960). A revised soil map at 1:500,000 scale with 31 mapping units consisting with combinations of different great soil groups was also produced by them (Fig. 4.4).

The mapping units were categorized to soils occurring in the dry zone and semidry intermediate zone and wet zone and semi-wet intermediate zone and miscellaneous land units. The soil map produced was at reconnaissance level at a scale of 1:500,000, where the mapping units consist of soil associations and complexes.

4.3.3   The Present Era (from 1972 to Date)

At the beginning of the present period, Dimantha (1977) surveyed the soils of the low-lying areas, bog soils, half-bog soils and alluvial soils. Panabokke and Somasiri (1980) classified the rice-grown soils of the wet zone of Sri Lanka from the highest elevation to the lowest elevation into four categories, namely, land system, land subsystem, land complex and land element. The next milestone of soil survey and classification was the initiation of the Sri Lanka-Canada Soil Resource Project (SRICANSOL Project) in 1999, which was a twinning project between the Soil Science Societies of Sri Lanka and Canada to classify the soils of Sri Lanka according to the international methods and map them. The soils of the wet, intermediate and dry zone were studied in detail, classified according to the international systems of soil taxonomy (Soil Survey Staff 2010) and the Food and Agriculture Organization method (FAO 1998, 2014). The soils were also mapped in detail than before where the wet zone was mapped at 1: 1:250,000 (Mapa et al. 1999, Fig. 4.5), the intermediate zone at 1:400,000 scale (Mapa et al. 2005) and the dry zone at 1:500,000 scale (Mapa et al. 2007).

These soil maps developed at soil series level (with map units as consociations, associations and complexes) overcame some of the weaknesses of the previous work. A soil series was defined as a soil having similar genetic horizons immaterial of the depth intervals. A benchmark site represented each soil series with the GPS location, description of the soil profile according to FAO method and colour photos

Fig. 4.4 Soil map showing the great soil groups of Sri Lanka (Adopted from De Alwis and Panabokke 1972)

Fig. 4.5 Soil map of the wet zone of Sri Lanka showing the soil series (Adopted from Mapa et al. 1999)

of the soil profile and landscape. In addition, a database comprising of selected soil's physical and chemical properties for each horizon was also made available. The soils also were classified according to the international methods as soil taxonomy (Soil Survey Staff 1998) and FAO method (FAO 1998).

These maps have been used for practical applications as potential risks on groundwater contamination with herbicides (Adikaram and Kumaragamage 2002), for re-demarcation of conservation area in Sri Lanka based on soil erosion potential (Munasinghe and Pushpakumara 2002), to estimate organic carbon stocks in rubber (*Hevea brasiliensis*)-grown soils of Sri Lanka (Dharmakeerthi 2013) and to predict the soil organic carbon in soils of Sri Lanka (Vitharana et al. 2017a).

4.4   Digital Soil Mapping

Generation of detailed soil information for specific purposes such as for precision agriculture, process-based earth systems models, environmental studies and assessing climate feedbacks is a challenge faced by soil scientists (Lagacherie and McBratney 2007). The qualitative nature of the empirical predication models used in the traditional soil survey limits its suitability for detailed soil mapping (McBratney et al. 2003). Nonetheless, such conceptual models are not capable of utilizing geo-computational capabilities in geographic information systems (GIS). In the last two decades, digital soil mapping (DSM) evolved as an alternative for traditional soil survey-based mapping. Advances in information technology, spatial computation methods, proximal and remote sensing technologies and satellite-based navigation techniques have largely contributed to the evolution of digital soil mapping which is defined as "the creation and population of spatial soil information by the use of field and laboratory observational methods, coupled with spatial and non-spatial soil inference system" (Carré et al. 2007; Lagacherie and McBratney 2007). Digital soil mapping techniques are used to predict the spatial variability of soils either in the form of choropleth or continuous soil maps (Fig. 4.2). Geographic information systems play a key role in DSM by providing a platform to store, manage, analyse and display soil spatial information.

Jenny (1941) described the formation, thus the variability, of soils in relation to the "five factors of soil formation". This pedologic model is expressed as follows:

$$S = f\left(cl,o,r,p,t\right)$$

where properties of a soil (S) at a location is considered to be a function of climate (cl), organisms (o), relief (r) and parent material (p) interaction over time (t).

Addressing the present-day geo-computational computation options available for spatial data analysis, McBratney et al. (2003) modified Jenny's *clorpt* model to be used for quantitative prediction of soil variability:

$$S = f\left(s,c,o,r,p,a,n\right)$$

where soil (S) is a function of soil information (s) and its spatial relationship (n) with climate (c), organisms (o), relief (r), parent material (p) and age (a). This model highlights the need of georeferenced soil information and its relationship with environmental controllers of soil variation to predict the spatial distribution of soils.

4.4.1 Use of Ancillary Information for Digital Soil Mapping

Construction of spatially accurate detailed soil maps requires the collection of a large number of soil samples and subsequent laboratory analysis which are time-consuming and cost prohibitive. However, digital soil mapping makes use of the quantitative information of secondary variables to map the spatial variability of soil properties or classes. This information is referred to as exhaustive ancillary information. The need of lesser number of soil samples allows the creation of detailed soil maps in a cost-effective manner by combining with ancillary information. Different sampling approaches have been suggested for DSM. De Gruijter et al. (2006) recommended model-based sampling approaches such as centred grid sampling, spatial coverage sampling and geostatistical sampling as suitable soil sampling approaches for DSM. The conditioned Latin hypercube sampling (cLHS) is a novel approach developed by Minasny and McBratney (2006) as a method for soil sampling in the presence of ancillary information such as digital elevation models, remotely sensed images and proximally sensed soil information.

The use of cLHS allows choosing sampling locations adequately representing the parameter space of information represented by environmental covariates used for the prediction of soil properties. Remote sensing provides high-resolution information suitable for digital soil mapping. Kumar et al. (2016) combined land use/land cover information derived from AVNIR satellite data (10 m resolution) with other information such as slope, geomorphology and soil types to generate groundwater potential zones in Kilinochchi area. Muthuwatta et al. (2001) used NOAA-AVHRR sensor data to estimate soil moisture in Walawe basin of Sri Lanka at 1 km resolution. Rathnayake et al. (2016) reported that Landsat 8 satellite images can be used to predict soil organic carbon concentration in paddy-grown soils of the northern region of Sri Lanka. Vegetation indices such as the normalized difference vegetation index (NDVI) have widely been used for spatial characterization of soils in relation to the type of vegetation cover. Soil information obtained using invasive and noninvasive proximal soil sensors have proven to be useful for digital mapping of soils (Adamchuk et al. 2004), since these methods can detect the properties of materials below the soil surface. Compared to conventional techniques in the collection of soil information, proximal sensing methods are less expensive, more rapid and provide larger amounts of data for the area covered (Brevik et al. 2015). These methods can be applied in the field using portable devices (Doolittle and Brevik 2014). Soil sensors can be interphased with a global positioning system (GPS) receiver and manually operated to obtain georeferenced measurements on the go. Thus, a large number of observations can be taken with less field sampling effort. The potential of electromagnetic induction-based proximal soil sensing for digital mapping of soils of Sri Lanka has been well explored. Rathnayake et al.
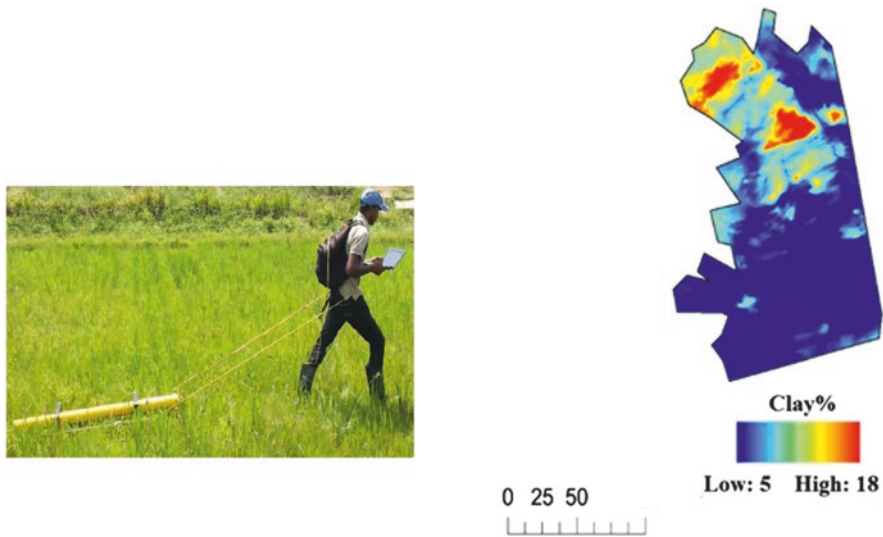
Fig. 4.6 Proximal sensing of paddy-grown soil using the DUALEM-1S sensor (left) and detailed clay content map constructed using ECa data (right)

(2017) used the DUALEM-1S sensor for detailed mapping (1 m resolution) of soil texture in a 2.5 ha paddy land (Fig. 4.6) belonging to Batalagoda soil series (Typic Endoaqualfs).

Hiranthika et al. (2015) elucidated sodic and saline soils using proximal soil sensing, and Perera et al. (2015) mapped salt-affected paddy-grown soils in Anuradhapura area. Further, Vitharana et al. (2013) reported differential behaviour of proximal soil sensing on red yellow podzolic soils (Ultisols) and reddish brown earth soils (Alfisols) and stated EMI-based proximal sensing is highly suitable to map soil texture in Alfisols of Sri Lanka. Vitharana et al. (2014) successfully elucidate soil texture and depth to the gravel layer using the DUALEM-1S sensor measurements. Other proximal soil sensors such as visible and near-infrared (Vis–NIR) spectroscopy, ground-penetrating radar (GPR), soil pH sensing and gamma-radiometric (γ) soil sensing have been successfully used in other countries to map soil physicochemical properties (Table 4.2). However, the potentials of these latest proximal soil sensors to characterize the soils of Sri Lanka are yet to be explored.

The availability of digital elevation data has opened up new possibilities for incorporating quantitative topographic information for supporting soil map preparation. Topographic attributes derived from square-grid digital elevation models (DEMs) have often been used as ancillary information for the spatial prediction of soil properties. Sources of elevation data for DEM creation can be from field measurement of elevations using theodolites, GPS receivers and digitization of contour lines on paper maps or data collected using airborne altimetry. Digitized contour data at 1:10,000 scale available with the Survey Department of Sri Lanka are excellent source of information for the development of DEMs.

Table 4.2 Available proximal soil sensing techniques for prediction of different soil properties (modified from Whelan and Taylor 2013)

Soil properties	Proximal soil sensing technique
Soil nutrients—N, P, K, S and trace elements	Visible (VIS)/near-infrared (NIR)/short-wavelength infrared (SWIR)/mid-infrared MIR spectroscopy Ion-selective electrodes Ion-selective field-effect transistor (ISFET)
Soil pH	Ion-selective electrodes ISFET VIS
Organic matter	VIS/NIR/SWIR/MIR spectroscopy
Soil sodicity	Electromagnetic induction (EMI) Resistivity
Soil salinity	EMI Resistivity Ground-penetrating radar
Soil texture/soil type	Gamma-radiometrics EMI Resistivity Visible/NIR/MIR Spectroscopy Ground-penetrating radar Tillage draft
Soil water storage capacity (PAWC)	EMI Resistivity VIS /NIR/MIR/thermal IR spectroscopy Radar
Rooting depth	EMI Resistivity Ground-penetrating radar

Moreover, scientists have the free access to global digital elevation data at a spatial resolution of 30 m through the NASA Shuttle Radar Topography Mission (SRTM) database (Farr et al. 2007). Primary topographic attributes such as slope and specific catchment area and secondary topographic attributes such as wetness index and stream power index derived from a DEM (Wilson and Gallent 2000) can be used as ancillary information for predicting soil properties (Vitharana et al. 2008). Jayakody et al. (2015) explored topographic-soil relationships to support spatial prediction of soil properties in a red-yellow podzolic soil scape in the wet zone of Sri Lanka. Vitharana et al. (2017a, b) showed the potential of the SRTM-based DEM as a covariate for digital mapping of soil K concentration in Sri Lanka (Fig. 4.7).

The development of national-level inventories of soil organic carbon stocks and monitoring are imperative for assuring the sustainability of the soil resource and minimize negative feedbacks on climate change. Vitharana et al. (2019) found topography of Sri Lanka modelled using the SRTM as a strong environmental controller of the spatial distribution of soil organic carbon stocks and used primary and secondary topographic attributes to produce detailed maps at a spatial resolution
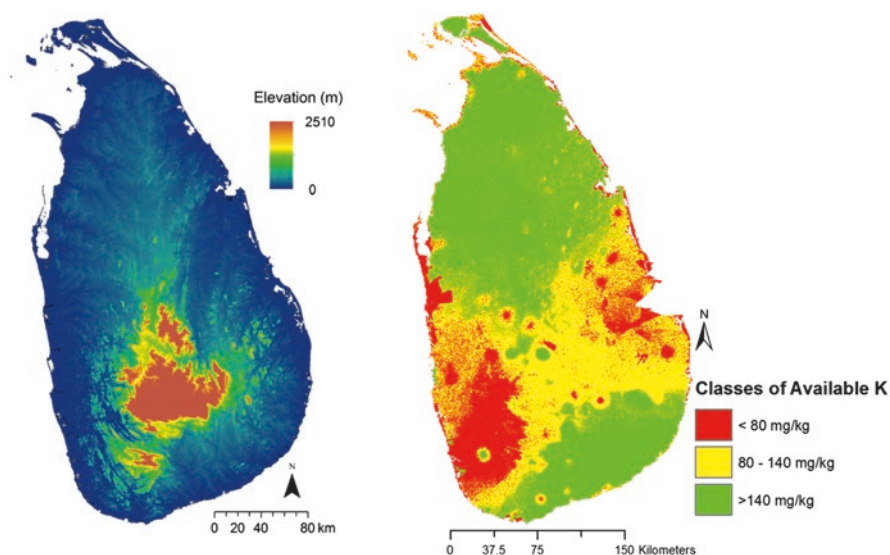
Fig. 4.7 SRTM data-derived DEM (left) and a digital maps of availability classes K (right) in Sri Lanka

of 30 m. They showed that information derived from legacy soil maps of Sri Lanka can improve soil organic carbon prediction models. Digital elevation models allow automated delineation of (sub) catchment areas. This intern is very useful to model soil formation process within a catchment scale and produce detailed soil maps. Vitharana et al. (2008) used digital elevation model to elucidate the soil variability, considering erosion and sedimentation processes at sub-catchment scale in a temperate soil-scape.

Such studies are yet to be performed under local conditions. Dobos et al. (2010) highlighted the potentials of original soil data collected in national soil survey and soil fertility assessment campaigns for digital soil mapping. These legacy data have been used in many countries for soil mapping. Vitharana (2017) fitted mass-preserving depth splines (Bishop et al. 1999) to soil profile data ($n = 122$) to extract soil organic carbon and bulk density data for soil depths 0–30 cm and 30–100 cm of soils of Sri Lanka. Digital maps of surface and subsurface soil carbon and K stocks (Fig. 4.7) of Sri Lanka were derived from these data by applying digital soil mapping techniques.

4.4.2 Use of Pedometric Models for Soil Mapping

Quantitative spatial prediction models play an essential role in digital soil mapping. In situations where ancillary information is available, these models need to be capable of combining sparsely measured soil properties with exhaustive ancillary information to produce digital soil maps. Pedometrics (McBratney et al. 2003),

which is defined as "the application of mathematical and statistical methods for the quantitative modelling of soils, with the purpose of analysing its distribution, properties and behaviors", encompasses these spatial prediction models. Hiranthika et al. (2015) used multiple regression to map soil salinity of a paddy-growing soil, and Wijesinghe et al. (2018) applied the classical statistical method, Fuzzy *k*-means classification, to refine the soil boundaries of a choropleth soil map (1:10,000) of an agricultural experimental station in Sri Lanka. Geostatistical methods are developed on the basis of the theory of regionalized variables. These methods quantify the spatial structure of variables by calculating the experimental variogram and subsequent fitting of a variogram model. The variogram explains the nature, the scale and the magnitude of the spatial structure. Then, the variogram is used for interpolation (known as kriging) of soil information (Webster and Oliver 2007). Kriging provides the best unbiased linear estimate (BLUE) of a soil attribute. Rosemary et al. (2017) reported the presence of strong spatial structure of soil pH, EC, organic carbon and CEC within a soil catena in Sri Lanka. Further, they used kriging to produce detailed digital maps (spatial resolution = 1 m) of these properties within the catena (Fig. 4.8).

Rathnayake et al. (2015) studied the variability of soil chemical properties of rainfed lowland paddy fields using inverse distance to power interpolation technique, and they concluded that the variability of soil available P, K, pH and EC is structured enough to guide site-specific application of soil management practices. On the basis of maps of available P developed for the Polonnaruwa District, Rathnayake et al. (2015) reported that considerable reduction of usage of inorganic P fertilizers can be achieved by utilizing these maps.

Hybrid methods combine classical statistics and geostatistical methods in order to use ancillary information for soil property estimation (Webster and Oliver 2007). Cokriging considers the joint spatial variability (co-regionalization) between ancillary information and soil properties to estimate the latter (Webster and Oliver 2007).
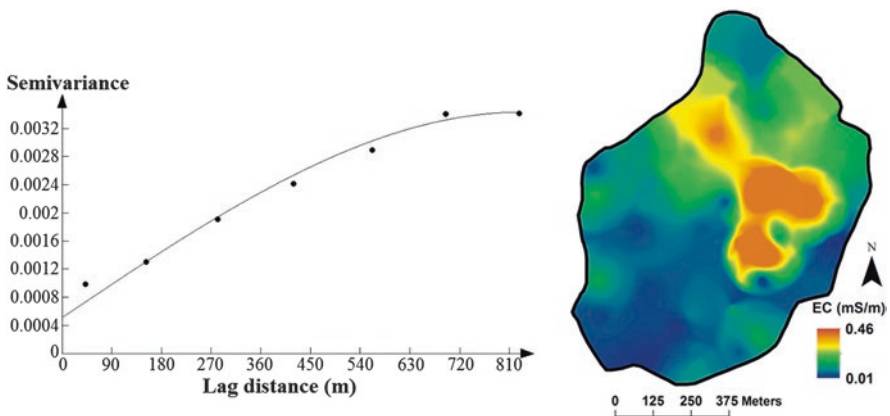

Fig. 4.8 Variogram showing highly structured variability of soil EC in a dry zone catena (left) and a digital soil map of soil EC (dS m^{-1}) within catena (right, source Rosemary et al. (2017))

Rathnayake et al. (2017) used cokriging to predict soil texture in a rice-grown soil using proximally sensed ECa as an ancillary information. They found a strong co-regionalization between soil textural fractions and ECa. Regression kriging combines linear regression models with ordinary or simple kriging of residuals (Hengle et al. 2007). Rathnayake et al. (2017) found greater accuracy of predicting the soil texture of paddy-grown soil by regression compared to cokriging. Vitharana et al. (2019) found geographically weighted regression kriging approach as a suitable method for digital mapping of soil organic carbon stocks across the island.

The recent studies on soil mapping in Sri Lanka reveal a gradual shifting towards nationwide digital soil mapping. It can be expected that comprehensive detailed digital soil information system should be developed in the future, assuring the sustainable use of soil resource amid the constraints of limited availability of lands, higher food demand due to the ever-increasing population growth and negative feedbacks on the national food production due to extreme climatic events.

4.5   Future Directions of Soil Survey and Mapping in Sri Lanka

The need of soil information has expanded beyond its classical uses, and presently soil information is vital for addressing environmental issues, food security, energy security, water security and human health (Brevik et al. 2015). According to Mermut and Eswaran (2000), this has led to the emergence of new areas of interest such as land and soil quality, recognition of problems of land degradation and desertification, cycling of biogeochemical and soil pollution assessment and monitoring. These requirements are driving new demands for better soil maps at finer resolution. Soil survey and mapping priorities of any country need to be focused on the present and future needs of soil information. Sri Lanka went through a successful era of soil survey, classification and mapping; these legacy soil maps have primarily served for agricultural purposes at its best. Lack of details resulted by the coarse cartographic scale and qualitative nature of the spatial model used limits the use of these legacy soil maps of Sri Lanka for many applications at present. According to classification proposed by Rossiter (2000), soil maps available in Sri Lanka belong to a very low intensity level (Table 4.3), thus less appropriate for moderately intensive uses such as farm-level planning and district-level planning and for intensive uses such as site planning, precision agriculture and urban land use planning. Therefore, there is a need of a soil survey and mapping in Sri Lanka at a more detailed scale. Improvements of technology pertaining to digital soil mapping have allowed making better soil maps. Catering the present soil information demand, the next national soil survey needs to be performed at a scale of 1:25,000 or larger.

The classification-based mapping legend that is presently used is merely useful for the present-day quantitative soil information needs. Thus, soil properties-based map legend will be more appropriate. The multidisciplinary nature of the usage of soil information requires a collective decision of scientists on the soil properties to be considered for future mapping activities. Further, with the progress of digital soil mapping, the soil survey and mapping have been shifted from a solitary activity carried out by small soil survey teams with similar level of skills to an endeavour

Table 4.3 Classification of soil survey types according to cartographic scale and sampling intensity (modified from Rossiter 2000)

Intensity level	NRCS 'Order'	Observation density	Scale of publication scale	Minimum legible delineation	Purposes
1. Very high (intensive)	1st	>4 per ha	1:2500	0.025 ha	Site specific soil management, detailed engineering, precision agriculture
2. High (intensive)	1st	1 per 0.8 ha to 4 ha	1:10 000	0.4 ha	Experimental site planning, intensive uses, urban land use planning
3. Moderately high (detailed)	2nd	1 per 5 ha to 25 ha	1:25 000	2.5 ha	General agriculture, detailed project planning, urban planning
4. Medium (semi-detailed)	3rd	1 per 20 ha to 100 ha	1:50 000	10 ha	Moderately intensive uses at farm level, community planning, district level planning
5. Low (semi-detailed)	4th	1 per 100 ha to 400 ha	1:100 000	40 ha	Extensive land uses, project feasibility, regional land inventory, district-level planning
7. Very low (reconnaissance)	5th	<1 per 100 ha	1:250 000	250 ha	National land inventory, regional planning, very extensive land use
Exploratory		Opportunistic	1:1 000 000 1:5 000 000	4000 ha 100,000 ha	General information on unmapped areas

requiring a number of professionals with different skills, including soil surveyors, pedomatricians, GIS specialists, computer programmers and remote and proximal soil sensing experts (Lagacherie and McBratney 2007). Thus, there is a need of establishing a consortium of such relevant professionals before undertaking a national-level soil mapping project in the future.

The limitations of available arable land resources exert heavy pressure on existing agricultural lands to increase the productivity at a minimum cost to the environment. Adoption of advances of precision agriculture technology is one of the viable options to achieve present agricultural production targets while minimizing the overutilization of finite natural resources and the detrimental environmental impacts of associated agrochemical pollutants. Precision agriculture (farming) is defined in the literature in different forms, and according to Pierce and Nowak (1999), the application of technologies and principles to manage spatial and temporal variability associated with all aspects of agricultural production for the purpose of improving crop performance and environmental quality. Site-specific crop management is a form of precision agriculture whereby decisions on resource application and agronomic practices are improved to better match soil and crop requirements as they vary in the field (Whelan and Taylor 2013; Vitharana 2008). Site-specific application of fertilizers, irrigation and soil improvement is relying on detailed and quantitative maps (Table 4.3) of soil attributes. Though isolated attempts have revealed (e.g. Rathnayake et al. 2017) the presence of highly structured short-scale spatial variability of soils of Sri Lanka that suit for site-specific soil management, extensive mapping of key soil properties required for site-specific soil management (Vitharana et al. 2008) needs to be conducted covering soils used for agricultural production. These maps could be used to delineate management zones to practice site-specific nutrient management, tillage practices and irrigation for major crops including rice. Presently, researchers from the Department of Soil Science of the Faculty of Agriculture, University of Peradeniya, Sri Lanka are in the process of calibrating a decision support tool for supporting site-specific management of nutrients for paddy, which requires detailed information of soil properties for site-specific fertilizer recommendations.

Global initiatives such as 4 per mille (Lal 2016; Minasny et al. 2017) and Land Degradation Neutrality (LDN) in 2030 (United Nations General Assembly 2015) targeted to combat climate change, and land degradation impacts are relying on accurate and detailed inventories of soil organic carbon at national level. Detailed spatial inventories of forest soil organic carbon stocks and establishing observational networks (Vitharana et al., 2017b) for monitoring are prerequisites for C credit initiatives. Vitharana et al. (2019) attempted to generate a map of soil organic carbon stocks using organic carbon data extracted from 122 soil profiles from SRICANSOL database and the recently inventoried database of benchmark soil profiles (Mapa 2016), representing the soils of the northern region of Sri Lanka. The use of advanced digital soil mapping techniques allowed them to generate an acceptable estimate of soil organic carbon stocks in surface (0–30 cm) and subsurface (30–100 cm). However, a considerable uncertainty of estimates has been reported which was resulted due to the limitation of soil observations, and it has been recommended for the nationwide digital soil mapping with larger soil observation network comprised of 1552 samples.

Soil acts as a source and a sink for many pollutants including trace elements (Helmke and Losco 2013). Interactions between soils and groundwater contamination and consequent environmental and health issues became a major concern of the latter stage of the twentieth century (Hartemink 2002). Thus, maps of baseline concentrations of soil pollutants are a requirement to assess the present status and establish monitoring programs to sustain the environmental integrity. Sanjeevani et al. (2015) attempted to establish baseline concentrations of some trace elements in a soil map unit of the dry zone of Sri Lanka. However, extension of such studies covering the entire nation with detailed digital maps is of urgent necessity.

Land degradation has become a severe problem of Sri Lanka (Nayakekorala 1998). Detailed assessment of soil erosion hazard is one of the major focus to avoid further degradation of the soil resource. Though many attempts have been undertaken to map soil erosion hazard, lack of information on soil erodibility causes greater uncertainty in hazard predictions. Therefore, generation of soil information, such as soil texture, structure and erodibility at a finer scale, would support accurate assessments. Further, the development of suitable soil attribute indices to recognize marginal lands and mapping of such lands are important to undertake proper rehabilitation activities.

Though numerous information acquisition methods, sources of secondary information and pedometric techniques representing quantitative pedologic models are presently available for soil mapping (Minasny and McBratney 2016), the requirement of sufficient soil sampling and analysis remains. This is often seen as a constraint in developing detailed soil maps due to cost and time involvement. Therefore, national-level policy decisions are required for allocating adequate funding for prospective soil survey and mapping projects. Further, the legacy soil information from existing soil maps and profile databases (e.g. SRICANSOL database) needs to be utilized for digital soil mapping. Soil map predicts the geographical distribution of soil properties or soil classes and involves an uncertainty. Present uses of soil information such as for process-based models require quantitative information on the uncertainty of soil maps. Therefore, future endeavours of soil mapping should include uncertainty assessment of survey products. Brevik et al. (2015) highlighted that soil information has to be more easily comprehended to raise awareness about the importance of soil for sustainable land use and be focused on important environmental problems. Advances of information technology can be used to present soil maps and information that can be accessible to all. The development of web-based spatial soil information system (SSINFOS) (Lagacherie and McBratney 2007) is one of the viable options to present digital soil information of Sri Lanka in the future.

4.6   Conclusion

The history of soil survey, classification and mapping in Sri Lanka exemplifies the gradual advancement of inventorying soil information for agricultural purposes. These maps and the databases have primarily served for agricultural planning and management at its best. However, the need of soil information has expanded beyond its classical agriculture-based uses and has become a prerequisite for addressing

environmental issues, food security, energy security, water security and human health. These requirements have driven new demands for better national soil maps at a finer resolution. Addressing these demand, the next national soil survey needs to be performed at a scale of 1:25,000 or larger using soil properties-based map legend. The multidisciplinary nature of the usage of soil information requires a collective decision of scientists on the soil properties to be considered for future mapping activities. Ultimately, the development of web-based national spatial soil information systems is a viable option to publish the next-generation digital soil information of Sri Lanka.

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