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Remote Sensing in Soil Fertility Evaluation and Management

(*Sangeeta Danga and Narendra Danga)
Central Arid Zone Research Institute, Jodhpur, Rajasthan, India
*Corresponding Author's email: sdsd675314@gmail.com

Soil is a complex material that is extremely variable in its physical and chemical composition and is formed from exposed masses of partially weathered rocks and mineral composing the earth's crust. Soil formation is strongly dependent on the environmental conditions of both the atmosphere and the lithosphere. The soil body is a product of factors (Dokuchaev, 1883 and Jenny, 1941) like climate, time, organisms, and topography and parent materials. The interactions of these factors result in great variability in soils (Buol et al., 1973). The upper soil horizon may contain valuable information about the soils, such as soil degradation processes, salinity, organic matter, crust formation, soil moisture, soil run-off and infiltration, which may be mainly utilized for evaluating the soil fertility using the Remote Sensing techniques. Remote Sensing means acquiring information by using satellites and spacecraft about a phenomenon object or surface at a remote vantage point without making physical contact with the object or subject.

Electromagnetic Radiation (EMR) and Earth's Surface

Radiation from the sun, when incident upon the earth's surface, is either reflected by the surface, transmitted into the surface or absorbed and emitted by the surface interfered by the constituents of atmosphere known an Atmospheric Effects". The EMR, on interaction, experiences a number of changes in magnitude, direction, wavelength, polarization and phase. These changes are detected by the remote sensor and enable the interpreter to obtain useful information about the object of interest. The remotely sensed data contain both spatial information (size, shape and orientation) and spectral information (tone, color and spectral signature). From the point of view of interaction mechanisms, the wavelengths (visible and infrared) from 0.3 µm to 16 µm can be divided into three regions. The spectral band from 0.3 µm to 3 µm is known as the reflective region. In this band, the radiation sensed by the sensor is that due to the sun, reflected by the earth's surface. The band corresponding to the atmospheric window between 8 µm and 14 µm is known as the thermal infrared band. The energy available in this band for remote sensing is due to thermal emission from the earth's surface. Both reflection and self-emission are important in the intermediate band from 3 µm to 5.5 µm.

Indian Space Programme

The Indian Space Programmed has started in 1979 with the experimental satellites Bhaskara-1 and 2, which carried TV Cameras and Microwave Radiometers. The Indian Remote Sensing Satellite (IRS) was the next logical step towards the National Operational Satellites, which directly generates resource information in a variety of application areas such as agriculture, forestry, geology and hydrology. IRS -1A/1B, carried Linear Imaging Self Scanning sensors LISS-I & LISS-II. IRS-P2 was launched in 1994 on PSLVD2, an indigenous launch vehicle. IRS-1C was launched in 1995, which carried improved sensors like LISS-III, WiFS, PAN Camera, etc. IRS-P3 was launched into the sun synchronous orbit by another indigenous launch vehicle PSLV-D3 in 1996 from Indian launching station Sri hari Kota (SHAR).

Remote Sensing and Soil Properties

For agricultural purposes the satellites should have the ability to provide repetitive coverage on a daily basis or 5 to 10 days intervals and spatial resolutions of 5-20 m, frequent coverage of 2-5 days and rapid data delivery to the user. Aircraft platforms have ability of acquiring the data in spatial resolution of 1 to 5 m range because of smaller sensor viewing areas. But the satellite data obtained from fixed orbits provide no data during cloud cover and have higher cost considerations when acquiring data within a narrow, specific timeframe. However, the remote sensing has a great potential to provide soil and crop information, therefore, the delineation of suitable management units is an important aspect for site specific crop management. Remote sensing has ability to generate images to show the spatial variation in fields caused by natural and cultural factors thus avoiding dependency on costly sampling intervals or geo-statistical interpolations.

Spectral Reflectance of Soils: The spectral reflectance properties of soils are fundamental to many applications of remote sensing in soils. The soil reflectance data can be acquired in the laboratory or in the field and from air/space. The study of spectral reflectance of soils has ability to provide non-destructive rapid prediction of soil physical, chemical and biological properties (Ben-Dor *et al.*, 1997). The vegetation spectral response can also be used to infer various soil conditions such as water-holding capacity, eroded locations and nutrient differences. Most of the passive remote sensors can provide information about soils from reflectance spectra in the visible (0.40 μm to 0.70 μm), near infrared (0.70 to 1.10 μm) and short wave infrared (1.10 to 2.50 μm) regions of electromagnetic.

Soil Mapping

In early days, Multispectral Remote Sensing data were considered of limited use because the evaluated results were compared with existing soil maps generated by conventional methods. The low accuracy attributed to remotely sensed data when compared with existing soil maps was the result of the assumptions that (1) the conventionally prepared soil map is 100% correct, and (2) that the spectral response of the soil surface is determined by the same morphological features used to derive the soil survey maps. With the more recent emphasis on intensive, precision farming, producers

Remote Sensing and Soil Fertility

It is very well known fact that soil variability influences the production potential of soil and to check that the soil sampling is done in small representative blocks or grids. The soil samples acquired at coarse and/or variant resolutions are interpolated to obtain average soil characterization values at a given finer resolution to make relevant management decisions. Such interpolation is done using geo-statistical analysis based on k ringing or inverse-distance weighting. The drawbacks of geo-statistical analysis include the need for a large number of samples at close sampling intervals and the assumption of stationary data variation, which is often not the case for soil properties. Remote sensing offers the potential to overcome these drawbacks. Early work using visual interpretation of Landsat images provided overlays with acetate transparencies of soil map sheets to investigate relationships of Landsat multispectral data to soil patterns. Although the results vary by geographic regions, there is agreement that the use of satellite or airborne imagery decreases the time required in soil survey and mapping period and therefore reduces costs. Spectral classification alone cannot distinguish between widely differing soils exhibiting similar spectral responses. By adding ancillary data, a more detailed delineation of soils can be provided as compared to information derived solely from Landsat data. However, these comparisons also reveal some discrepancies between spectral soil maps produced from Landsat data and conventional soil survey maps.

Soil Fertility Evaluation: The main components of soil fertility addressed with remote sensing include organic carbon, soil nitrate levels, soil clay content and thickness. Among plant nutrients, nitrogen is one of the most important factors in maximizing the crop yields and economic returns to farmers. The spatial variation in nitrogen content has been addressed using crop vigor as a proxy indicator, in-field referencing of point in question with a point of known nitrogen status, spatial interpolation of soil analytical data using remote sensing data as guiding force for interpolation. Although data from currently operational reflectance sensors such as Landsat, SPOT and a host of other public and private sensors have proven useful for crop identification and wetland inventory, attempts to characterize soils have attained only limited success. The major difficulty in deriving soil information from remotely sensed data is the complex nature of relationship between soil parameters and reflectance. Organic matter, moisture, texture, cation exchange capacity (CEC), mineral oxides and surface conditions such as residue cover and soil crusting have demonstrated unique influence on soil 516 Bio resources for Sustainable Plant Nutrient Management reflectance. These relationships are wavelength-dependent; therefore, the soil parameters may affect reflectance differently in different regions of the spectrum.

Organic Matter: Accurate and timely information about soil organic matter is essential for agricultural production and environmental research. During the past three decades, high altitude remote sensing coupled with laboratory based reflectance spectroscopy has emerged as an important technology for monitoring the Earth's agricultural resources. The soil spectral responses due to soil colour have long been associated with native soil fertility and are also useful in determining the soil organic matter: 1. the soils of higher organic matter content are generally darker in colour and are less reflective than those soils with lower organic matter content. Soils with thick, dark surface horizons are often separated from other soils in many soil classification systems, which emphasize the importance of these soils both as a medium for plant growth and also as an indicator of land value for agricultural and urban area. 2. In glaciated soil regions, high organic soils can be readily differentiated in high-resolution satellite images from soils formed under prairie grass vegetation and soils formed under forest vegetation. 3. Bare soil areas with high-residue content from the previous crop may mask soil spectral responses. The use of high spatial digital terrain models (DEM) produced by remote microwave or laser techniques can provide a better understanding of soil formation and surface moisture movement and hence aid in interpreting surface soil organic matter content. Different methods have been developed for the calibration of soil organic matter sensors involving a given sequence of soils of about the same age, related parent material and similar climatic conditions, but characterized by variations in topography and drainage. Laboratory studies have measured soil reflectance, attempting to quantify the relationship between soil colour and organic matter content by comparing the soil spectra with soil Munsell values. The reflectance to specific organic matter components has been attempted in many investigations. Typically these studies fractionate organic matter into pools such as humic acid, fulvic acid and the remaining mineral components; then each fraction is analysed using a spectrophotometer. Even small amounts of organic material may be particularly effective in masking mineral features in the shorter wavelengths and the unfractionated soils and their mineral Remote Sensing in Soil Fertility Evaluation and Management 517 components have important influences on reflectance to examine organic carbon content in relation to other soil properties. To examine specific effects of organic carbon on soil reflectance, researchers have tested differing spectral response in separable bands in terms of observable soil properties such as sand, silt, clay, iron oxides, magnesium oxides and organic carbon. The separable bands of the inorganic fractions (in which the extractable organic matter and humic acid have been removed) are compared with the separable bands from the soils that are unfractionated. There is a direct relationship between organic carbon and soil reflectance in the sets of bands in question: as soil organic carbon increases reflectance decreases. The organic matter contained within the soil is the physical factor responsible for spectral differences in this set of bands.

Nitrogen Deficiency: In general, nitrogen deficiency causes a decrease in leaf chlorophyll concentrations, leading to an increase in leaf reflectance in the visible spectral 518 Bio resources for Sustainable Plant Nutrient Management region (400-700 ηm). However, several other stresses (pest and diseases) may also result in increased plant reflectance due to reduced amount of chlorophyll (Carter and Knapp, 2001). Osborne et al. (2002) showed the utility of hyper spectral data in distinguishing nitrogen and phosphorus at the leaf and canopy level, but the relationships were not consistent over all plant growth stages. Spectral reflectance peaks resulted from derivative analysis of spectral reflectance found to be good technique for stress detection. The position of the inflection point in the red edge region (680 to 780 ηm) of the spectral signature, termed as red edge position (REP), is affected by biochemical and biophysical parameters.

Plant Nutrition Status

Plants contain pigments which absorb photons from sunlight that are involved in photosynthesis and other photochemical processes. The leaf pigment absorbs the photons of certain wavelengths and can emit partially or fully of this absorbed energy as fluorescence at longer wavelengths. The magnitude of the fluorescence emission is inversely related to relative efficiency of plant photosynthesis and other biochemical systems. Fluorescence can also be an indicator of the relative concentration of certain plant constituents. This technique was successfully used in corn and soybean and differences between the fluorescence of healthy plants and plants deficient in the major plant nutrients N, P and K and the minor plant nutrients Ca, Mg, S, Fe and B have been detected (Chappelle et al., 1984). Using laser-induced fluorescence (LIF) and passive reflectance measurements in the laboratory McMurtrey et al., (1994) observed differences in maximum intensity of fluorescence at 440 ηm, 680 ηm and 780 ηm which were found related to different levels of N fertilization in corn.

Land Degradation

Land degradation implies temporary or permanent regression from a higher to a lower status of productivity through deterioration of physical, chemical and biological aspects. Development of degraded lands in India is one of the options available to increase food production for growing population and to restore the fragile ecosystem. India has 25% of the total agricultural land degraded. Remote Sensing in Soil Fertility Evaluation and Management 519 the physical processes which contribute to land degradation are mainly water and wind erosion, compaction, crusting and water logging. The chemical processes include salinization, alkalization, acidification, pollution and nutrient depletion. The biological processes are related to reduction of organic matter content in soil, degradation of vegetation and impairment of activities of micro flora and fauna. The degraded lands/wasteland can be categorized as eroded lands, undulating uplands with or without scrub, water-logged, saline/alkaline soils, degraded pasture lands, sandy areas, mining/ industrial wastelands, barren rocky/stony wastes/sheet rock areas, steep sloping areas and snow covered/ glacial areas. In mapping of land degradation at any scale the base map is prepared on-line visual interpretation of satellite data, development of legend, ground truth collection, analysis of soil samples, classification of degraded classes and finalization of maps in the light of field information and analytical data (Krishan et al., 2009).

Mapping Salt Affected Soils

Salt-affected soils reveal presence of salts in two different ways in remotely sensed data (a) directly on bare soil with efflorescence and salt crust; (b) indirectly by affecting condition / type of vegetation or soil moisture condition. Numerous remote sensing studies had been carried out for mapping and monitoring of salt-affected soils in northern India with variety of optical remote sensing satellite data such as LANDSAT- MSS & TM, SPOT and IRS – LISS: I, II, III and recently using IRS – LISS IV and Cart sat data. 9.1 Multispectral Remote Sensing Multispectral Remote Sensing data has been mostly used in mapping the degraded land types. Rao et al. (1991) and Dwivedi and Rao (1992) used post-monsoon (October month) and pre-monsoon (dry season) Landsat-TM data for delineating moderately saline-sodic soils from slightly saline-sodic soils. Singh et al. (1988) delineated two categories of sodic soils, viz., (i) moderately, and (ii) strongly to very strongly sodic soils. Dwivedi and Sreenivas (1998) carried out image transform analysis to delineate saline and alkali soils and further, for delineation of moderately saline-sodic soils from slightly saline-sodic soils, infrared band of Landsat TM data quite useful, however, to detect ability of such soils in the Indo-Gangetic alluvial plains of India is image scale dependent. LISS-II sensor of IRS-IB satellite to analyze the effectiveness of several indicators for the presence of salts, i.e. salinity indices, normalized differential salinity index and ratio of the signal received by the 520 Bio resources for Sustainable Plant Nutrient Management sensors in the 3rd spectral band to others. He had used two classification processes (COMPOSITE MODULE and ISOCLUST function of GIS IDRISI) that performed classification based on specifically created image. Both schemes have shown to perform good classification. Metternicht and Zink (2003) reviewed various sensors (e.g. aerial photographs, multispectral sensors, microwave sensors, video imagery, airborne geophysics, hyper-spectral sensors, and electromagnetic induction meters) and approaches used for remote identification and mapping of salt affected areas. Constraints on the use of remote sensing data for mapping salt affected areas are shown related to spectral behaviors of salt types, spatial distribution of salts on the terrain surface, temporal changes in salinity, interference of vegetation and spectral confusion with other terrain surfaces. Fernandez et al. (2006) have used Landsat – ETM to correlate soil characteristics with the spectral response of plant species and bare soils, integrating an algorithm to allow multi-scale mapping using remote sensors. A Combined Spectral Response Index (COSRI) was calculated for bare soils and vegetation by adjusting the normalized difference vegetation index (NDVI).

Hyper spectral Remote Sensing: Generally, hyper spectral remote sensing data can be used for quantitative mapping of organic carbon, salt concentrations, clay minerals and nutrient mapping. The hyper spectral data has been widely used in mapping the salt affected soils. Hyper-spectral image pixel vector generally contains more spectral information than does a multispectral image pixel vector. In many situations, such spectral information is valuable and crucial in data analysis. In order to capture and characterize the spectral properties vector provided in a single pixel vector by hundreds bands, two spectral similarity measures such as spectral angle mapper (SAM) and normalized Euclidean distance (NED) have been used in material identification of salt-affected soils. Whiting and the limited evaluation of the low altitude Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) data using specific spectral bands for identifying the soil salinity and organic matter. They used AVIRIS as the image data layer in developing terrain models to simulate the content and spatial extent of surface soil organic and inorganic carbon. DAIS - 7915 hyper-spectral airborne sensor data for quantification and generation of soil properties' maps of organic matter, soil moisture and soil salinity.

Soil Resources Study and Management

The soil classification systems used around the world are combinations of the needs of the people, the amount of the data available, training and the technology that was used. Using remote sensing techniques mapping the soils shows a positive influence on the Earth's surface. A unified global effort in soil survey and mapping was the FAO/UNESCO soil map of the world produced in the late 1960s, with a revised legend in 1988 at a scale of 1:50, 000,00 without making use of spatial technologies. But for modern farming practices, the soil surveys using soil taxonomy typically do not have sufficient resolution to capture natural soil variability in enough detail to support 'precision farming' recommendations, which is possible by technologies such as Remote Sensing, Geographic Information Systems (GIS) and Global Positioning Systems (GPS). With the increasing availability of both very high spatial and spectral resolution remote sensing data, the opportunity to redefine soil survey maps is an important benefit. Land evaluation provides a rational basis to analyses various soil, climate and land parameters to arrive at optimum solution to various problems of natural resources. In the field evaluation process GIS has become an important tool because it enables to integrate the complex decisions to be taken under multi-variant situations of the resource base and their dynamics. Land evaluation principle is based on matching the requirements of a land for specific use with the characteristics of inherent soil, climatic, topographic and other natural resources and is concerned with the assessment of land performance when used for a specific use. The major GIS applications relevant to soils are: crop suitability studies, land capability assessment, land irritability assessment, land productivity assessment, soil erosion modeling, irrigation water management in command areas, prioritization of sub-watersheds/micro-watersheds in a given watershed, soil suitability assessment for various purposes like specific crops, industries, forestry etc, to identify critical areas in watershed/ micro watershed, to generate optimal land use plans etc., quantification of soil loss, planning the urban development, reclamation planning of degraded lands.

Crop Suitability Studies: The sustainable crop production in any area depends on its climate, soil and site characteristics of the area. This can be achieved through evaluation of soils of a given area for their suitability to different crops considering the inherent soil properties, topographical features and climatic parameters independently as well as in combination.

Land Capability Assessment: The land capability assessment helps to use the land according to its capability and to treat it according to its need. Land is arranged in various capability classes by considering a large number of soil characteristics (texture, depth, permeability, salinity and alkalinity), associated land features (slope, erosion status, natural soil drainage and frequency of overflow etc.) and environmental factors (climate).

Land Irritability Assessment: The soil depth, slope, salt problem, stoniness, waterlogging etc. are some of the criteria used for irritability assessment. It is more relevant before introduction of irrigation in any proposed command areas. The soil maps are overlaid on slope maps and various criteria were given as weightages to derive mapping units in a GIS environment. Then based in irrigability criteria, the assessment of the area is made for their suitability for irrigation.

Land Productivity Assessment: The initial soil maps are prepared; the land productivity index (LPI) of the area is assessed with respect to crops, pasture, forest/trees. GIS tools were used for calculating LPI values for soil types and for deriving area weighted LPI values for soil mapping units and in the generation of Land Productivity Map for the study area.

Soil Erosion Modeling: The general approaches include a rule based approach where several parameters (slope, cover, soil erodibility, rainfall quantity and intensity and the soil conservation or management factor) that influence the soil loss are weighted and summed to assess the final index to rate a particular area for erosion status.

Prioritization of Watersheds: The main approaches for prioritization of watersheds are resource based, economy based and socio-economy based approaches. The problem of Remote Sensing in Soil Fertility Evaluation and Management 529 prioritization of watershed is objective oriented and the efforts are being made in the direction of development of methodologies that have more scientific rationale for development of watersheds and monitoring them in future.

Epilogue

The remote sensing technology for study of soil resources need to be employed on regular basis for mapping and monitoring soils at different scales. The stereoscopic satellite data in soil mapping has a great scope. Ground Penetrating Radars for soil survey are useful in classifying the soils and estimate the taxonomic composition of soil map units. Polari metric Synthetic Aperture Radar (SAR) data need to be explored for studying the spatial-temporal variation in soil moisture. The hyper spectral format contains up to several hundred wavelength bands and provides the potential for differentiating more specific soil properties. The current studies have used only three to four bands of data, which are very broad bands. The hyper-spectral bands would be very narrow in terms of the wavelength covered. The spectral mapping of specific soil properties will provide further assistance to soil pedologists in the development of soil surveys. Recent advances in precision farming technologies require an accurate representation of yield-limiting variables, which include soil properties. Producers have used soil type maps, as they are related to soil organic matter, to help in management practices such as fertilizer application, herbicide placement and seed spacing. When coupled with the adoption of global positioning satellites and geographic information system technologies, accurate soil organic matter maps allow for greater precision in performing management practices. Advances in remote sensing technology are providing a new way to monitor and study the soil properties and agricultural fields. The provision of geographically accurate soils data assists producers to adjust their application rates of fertilizers and pesticides according to soil properties. This helps producers to increase profits and to provide environmentally safer approaches for producing food.

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