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Remote sensing applications in soil survey and mapping: A Review

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ABSTRACT

This article reviews the use of optical, microwave, Lidar and hyper spectral remote sensing data for soil mapping with emphasis on applications at local and regional level. Remote sensing is expected to offer possibilities for improving incomplete spatial and thematic coverage of current regional and global soil databases. Soil properties that have been measured using remote sensing approaches include mineralogy, texture, soil iron, soil moisture, soil organic carbon, soil salinity and carbonate content. In sparsely vegetated areas, successful use of space borne, airborne and in situ measurements using optical, passive and active microwave instruments has been reported. On the other hand, in densely vegetated areas, soil data acquisition typically relied on indirect retrievals using soil indicators, such as plant functional groups, productivity changes, and Ellenberg indicator values. Several forms of kriging, classification and regression tree analyses have been used jointly with remotely sensed data to predict soil properties at unvisited locations aiming at obtaining continuous area coverage. Yet, most studies so far have been performed on a local scale and only few on regional or smaller map scale. Although progress has been made, current methods and techniques still bear potential to further explore the full range of spectral, spatial and temporal properties of existing data sources.

Keywords: soil survey, remote sensing, hyper spectral, lidar, review

1. Introduction

Soil is a fundamental natural resource; it is the basis of human agriculture. From an applied perspective, pedology and soil geography form the basis of soil survey, which remains the primary means by which information on the spatial properties of soil is collected, presented and archived in the USA and throughout the world. The United States Department of Agriculture (USDA), in cooperation with other federal and state agencies, began soil survey work in 1896. The combined state and federal government effort became known as the National Cooperative Soil Survey (Indorante et al., 1996).

More recently, however, soil maps have been used to provide chemical and physical data input within ecological and hydrological process models (Burrough and McDonnell, 1998: 163). The soil survey program was simply not designed to furnish data for such applications. The increasingly sophisticated use of soil data has led to a greater demand for data about soil properties than the conventional soil map can accommodate. Traditional soil survey concepts are based on qualitative recognition of soil properties in relation to landscape and environmental variables.

Soil systems like most natural systems, are in dynamic equilibrium. Most changes are slow and imperceptible particularly when viewed in the time frame of human lifespan. However, catastrophic events such as high intensity storms can accelerate erosion processes resulting in measurable changes. The changes are mainly in the structure and composition of the material and such changes are referred to as 'structural changes'. Changes are measurable directly or indirectly or may be inferred from behaviour of the system. Many of the changes are related to uses of the soil. These 'performance-related changes are more important as they can be quantified, particularly in economic value terms (Szabolcs 1994). An intimate knowledge of the kind of soils their spatial distribution is a prerequisite in developing rational land use plan for agriculture, forestry, irrigation, drainage etc.

Soil resource inventory provides an insight into the potentialities and limitation of soil for its effective exploitation. Soil survey provides an accurate and scientific inventory of different soils, their kind and nature, and extent of distribution so that one can make prediction about their characters and potentialities. It also provides adequate information in terms of land form, terraces, vegetation as well as characteristics of soils (viz., texture, depth, structure, stoniness, drainage, acidity, salinity and so on) which can be utilized for the planning and development. More than ninety percent of world's food production is dependent on soil (Venkataratnam & Manchanda 1997). The earliest proposals for study of soils of India on a nationwide scale can be traced back to 1940 when Rao Bahadur B. Vishwanath, and Imperial Agricultural Chemist, moulds the idea of taking up soil survey on a country wide basis with cooperation from soil scientists of the states. During 1948, Dr. A.B. Stewart of Macaulay Institute, Abreadeen carried out studies on fertility of Indian soils and submitted a report entitled "Simple Experiments on Cultivator's Field".

He suggested that soil survey based on soil climatic zones should be conducted so that a correlation could be made between soil types and crop yields. In the year 1954, Dr. F.F. Raickens, a soil specialist from USA was invited by Government of India to advice on soil survey work to be taken up in India. Based on the recommendations of Dr. Raickens, the All India Soil Survey scheme was initiated in 1956 at the Indian Agricultural Research Institute (IARI) with four regional centres located at Delhi, Calcutta, Nagpur and Bangalore to carry out reconnaissance soil survey, correlate and classify soils and prepare small scale soil maps. A soil survey manual describing the methods of conducting soil survey to suit our conditions was prepared and made available in 1960. A revised soil map of India was brought out in 1962 on the basis of soil survey and soil classification done by the State and Central Soil Survey Organization. During 1969, the All India Soil and Land use Survey Organization was bifurcated on the basis of developmental and research work. A new organization "National Bureau of Soil Survey and Land use Planning" was established in Nagpur. The establishment of Indian Photo interpretation Institute (IPI, now Indian Institute of Remote Sensing) in 1966 provided the training support to various soil surveyors on the use of aerial photographs. The initial soil surveys were based on either ground methods or through on a systematic aerial photo interpretation approach.

A number of studies on soil survey were carried out by various workers in India in different regions using aerial photographs. Use of satellite remote sensing for soil survey and mapping received appreciation during early 1980s in India, and based on the potential of remote sensing techniques it was decided to map all the States and Union Territories of India on 1:250,000 scale following a multiphased approach consisting of image interpretation, field survey, soil analysis, classification, cartography and printing (Velayutham 1999). The use of digital image processing for soil survey and mapping was initiated with the establishment of National Remote Sensing Agency and Regional Remote Sensing Service Centres. The initial works carried out by Venkatratnam (1980); Kudrat et al (1990) and Karale (1992) demonstrated the potential of digital image processing techniques for soil survey. A number of modelling studies were simultaneously carried out to derive a variety of information from soil maps, e.g. land evaluation, land productivity, soil erosion and hydrologic budget (Kudrat et al 1990; Saha et al 1991; Kudrat 1996; Kudrat et al 1995, Kudrat et al 1997).

Information on soils with regard to their nature, extent and spatial distribution along with their potential and limitations is required for a variety of uses, namely agricultural development, engineering, sanitary, recreation, aesthetic, etc. In addition, such information is also required for modelling and environmental impact analysis, viz. to determine run off and erosion using erosion simulation model (Laflen et al., 1991) or to determine agricultural chemical migration into ground water using a water quality simulation model (Chung et al, 1992). Furthermore, the study of the pedosphere is fundamental for a better understanding of the processes involved in global change (Ibanez et al., 1992). Soils can act as sources or sinks of the main greenhouse gases. Systematic soil surveys provide such information. Though non-renewable resource, the multiple usages of soils for meeting the increasing demand for food, fuel and fodder of ever growing population resulting in degradation of soil health, necessitates the updation of soil map at regular intervals.

Soil surveys are the main information source for land suitability assessment. Soil survey mapping units are defined by the soil properties that affect management practices, such as drainage, erosion control, tillage and nutrition, and they involve the whole soil profile (Soil Survey Division Staff, 1993). Soil is a valuable non-renewable resource and exists throughout the World in a broad diversity. Different types of soil exhibit diverse behaviour and physical properties. It provides essential support to ecosystems and to human life and society. Therefore, it is imperative to maintain soil functions and qualities to sustain the ecosystem and the human being (Blum, 1993; De Groot et al., 2002; European Commission, 2006). This alarmed authorities to plan and assess suitable parameters for land uses. It has been recognized that the quality of land suitability assessment and the reliability of land use decisions depend largely on the quality of soil information used to derive them (Mermut and Eswaran, 2001; Bogaert P, D'Or, 2002; Salehi et al., 2003; Ziadat, 2007).

2. Optical Remote Sensing in Soil survey and mapping

Satellite remote sensing data has emerged as a vital tool in soil resource survey and generation of information which help to evolve the optimum land use plan for sustainable development at scale ranging from regional to micro levels. One of the earliest studies in this field was carried out by Mirajkar and Srinivasan (1975) on 1:1 million scales through Landsat image interpretation. The task of gathering information on the soils has been greatly synergized by the enhanced speed and reliability with which spatial and temporal information is generated by remote sensing techniques, in a cost effective manner.

The surface features reflected on satellite image provide enough information to accurately delineate the boundaries which is accomplished effectively through systematic interpretation of satellite imageries. The properties of the soils that govern the spectral reflectance are colour, texture, mineralogy, organic matter, free carbonates, moisture and oxides and hydroxides of iron and manganese (Baumgardner et al., 1985). The information of these characteristic differences gathered by multi-spectral observation help to minimize traversing to a well planned ground observation sites for validating soil boundaries. Remote sensing may offer possibilities for extending existing soil survey data sets. The data it provides can be used in various ways. Firstly, it may help in segmenting the landscape into internally more or less homogeneous soil–landscape units for which soil composition can be assessed by sampling using classical or more advanced methods.

Secondly, remotely sensed data can be analysed using physically based or empirical methods to derive soil properties. Moreover, remotely sensed imagery can be used as a data source supporting digital soil mapping (Ben-Dor et al., 2008; Slaymaker, 2001). Finally, remote sensing methods facilitate mapping inaccessible areas by reducing the need for extensive time-consuming and costly field surveys.

Remote Sensing helps to overcome errors in locating and plotting soil boundaries as also in generating soil map of inaccessible or hazardous areas. The dynamic inter-relationship between physiography and soils is utilized while deriving information on soils from satellite data (Kudrat et al., 1992). The factors involved in physiographic processes more or less correspond to the factors of soil formation. In the interpretation of satellite image for soil mapping proper identification of land type, drainage pattern and drainage condition, vegetation, land use, slope and relief is very essential (Dwivedi, 2001). Often the raw image is not directly suitable for this purpose, and must be processed to improve the differentiation between various features and such processing is called image enhancement. Digital image processing, either as enhancement for human observers or performing autonomous analysis, offers advantages in cost, speed, and flexibility, and with the rapidly falling price and rising performance of personal computers it has become the dominant method in use.

Before the launch of Landsat-1 (in 1972), aerial photographs were being used as a remote sensing tool for soil mapping, and, exhibited their potential in analysing physiography, land use and erosion status. Subsequently, 1972 onwards satellite data in both digital and analog have been utilized for preparing small scale soil resource maps showing soil sub-groups and their association. The high resolution Landsat TM and Indian Remote Sensing Satellite (IRS) LISS II data which became available during mid eighties, enabled soil scientists to map soils at 1:50,000 scale, which is used for district level planning. At this scale soils could be delineated at association of soil series/family level. The SPOT and IRS -PAN data offered stereo capability, which has improved the soil mapping efforts. Indian Remote Sensing satellites (IRS-1A, 1B, 1C and 1D) provide state-of-the-art database for natural resources inventories. Many studies have been conducted to explore the potential of LISS-I and LISS-II data for soil resource mapping both at 1:250,000 and 1:50,000 scale. Several studies have been initiated on potential use of IRS-1C, LISS III and PAN data for mapping soils and it is expected that information on scale 1:25,000 to 1:12,500 scale could be generated through combination of these data (Kudrat et al 2000).

Use of digital imaging and associated geospatial information for characterizing and mapping soils is expanding rapidly with the advent of new sensors, aircraft and satellite platforms, ortho-rectification techniques, mathematical models for integrating disparate spatial data sources, and visualization of soil properties using conventional and web-enabled technologies (Mulders, 1987; Barnes et al., 2003; Mulder et al.,2011).

3. Thermal Remote Sensing in soil mapping

Thermal infrared remote sensing measures the thermal emission of the Earth with an electromagnetic wavelength region between 3.5 and 14 µm (Curran, 1985). Remote sensing is the process of inferring surface parameters from distant measurements of the upwelling electromagnetic radiation from the land surface (Schmugge et al., 2002). The radiation reflected or emitted by soil varies according to a range of chemical and physical characteristics of the soil matrix (Anderson and Croft, 2009; Barnes et al., 2003; Mulder et al., 2011; Schmugge et al., 2002; Tang et al., 2009). This makes it possible to discriminate between different soil surfaces when looking at specific wavelengths or combination of spectral bands. It is also possible to infer the properties of a known soil surface from variations in the measured radiation. For the reflected solar radiation, the most important characteristics of a soil that determine its reflectance properties are (Jones and Vaughan, 2010; Mulder et al., 2011; Stoner and Baumgardner, 1981):

Moisture: increasing soil moisture content decreases the reflectance in the water absorption bands but also in the remaining bands due to the internal reflections within the water film covering the soil particles; thus wet soils appear darker (less reflective) than dry soils.

Organic matter: increasing organic matter content gives darker (less reflective) soils;

Texture: sandy soils are more reflective than clay soils;

Surface roughness: decreases in surface roughness slightly increase reflection: an example is the development of soil crust;

Iron content: increasing the content of iron oxide corresponds for many soils to a change in colour towards their characteristic brick-red colour, which implies an increased reflection ion in the red and a decrease in green (Ben-Dor, 2002).

Some of the following problems can occur while mapping Soil from thermal remotely sensed data:

Identifying, categorizing and mapping soils can be a complex procedure which in many cases is based on soil properties that are not even visible to the naked eye and require field or laboratory analyses (e.g. pH).

Soil is a complex three-dimensional body. The majority of remote sensing systems only characterize the surface or, in optimum conditions, shallow depths of soils .In many cases, the surface characteristics may not be representative of the deeper soil body (e.g. soil organic carbon concentration decreases with depth).

Soil properties can vary dramatically both spatially and temporally within a small area.

The upper surface can be subject to frequent alteration by tillage, precipitation, erosion, crusting and other surface processes. Vegetation coverage obscures most soils for most or all the time. Soil subjected to arable cultivation will be exposed after ploughing. Soil under natural vegetation may never be exposed.

The signal recorded by sensor is the result of a combination of several soil properties (which are frequently interlinked). Such mixtures often mask the signal from a feature under investigation.

The spectral resolution of sensors is not suitable for mapping soil characteristics (i.e. not covering diagnostic regions of the spectrum, focused on observing vegetation).

3.1 Microwave remote sensing

Information of spatial and temporal variations of soil quality (soil properties) is required for various purposes such as soil and crop management for improving crop productivity; sustainable land use planning; soil erosion and runoff modelling in watershed management, precision agriculture etc.

Radar is known to be sensitive to several natural surface parameters such as vegetation, surface roughness and dielectric constant (e) (Bell et al., 2001). The dielectric constant is comprised of the permittivity or real part and the loss factor or imaginary part. Research studies indicated that soil salinity has no influence on the real part of the dielectric constant whereas the imaginary part is dependent and increases with increase in salinity for all three textured soils. (Ulaby et al., 1986; Sreenivas et al. 1995). Bell et al. (2001) used the airborne polar metric SAR for mapping soil salinity.

Several research studies showed that spatial variability of soil texture and hydraulic parameters could be assessed using temporal microwave remote sensing derived changes in brightness temperature and soil moisture content (Camillo et al. 1984; Mattikalli et al.1995; Mattikali et al. 1997; Mattikalli et al.1998; Chang and Islam, 2000; Santanello et al. 2007). The results of these studies indicated that close relationships existed between space-time evolutions of remotely sensed passive microwave brightness temperature and soil moisture and soil types with respect to soil textural class.

Application of Synthetic Aperture Radar (SAR) data and combinations of SAR and multispectral data has also been extensively studied within the context of improved landform recognition on a local scale (Madhavan et al., 1997; Singhroy and Molch, 2004). Different wavelengths of the SAR signal enable structural analysis of elements in specific size classes, while polarization angles are particularly sensitive for directional structures. Moreover, SAR is cloud-penetrating while the strength of backscatter depends on the dielectric properties of surface materials (e.g. soil water content), and the co polarization sensitivity to surficial sediments, both improve the classification of exposed surficial sediments (Singhroy and Molch, 2004).

4. Hyperspectral remote sensing of soils

Hyperspectral sensors (also known as imaging spectrometers) are instruments that acquire images in several, narrow, contiguous spectral bands in the visible, NIR, MIR, and thermal infrared regions of the EMR spectrum. Hyperspectral sensors may be along-track or across-track. A typical hyperspectral scanner records more than 100 bands and thus enables the construction of a continuous reflectance spectrum for each pixel.

Laboratory and field studies have revealed that certain soil characteristics exhibit characteristic absorption band, which could be used for their identification. For instance, soil water exhibit weaker absorption bands at 0.97, 1.2 and 1.77 um and prominent absorption bands at 1.4 and 1.9 um. (Bowers and Hanks, 1965). Similarly, gypsum and montmorillonite exhibit absorption bands at 1.8 and 2.3 um, and between 0.52 and 1.0 urn, respectively (Hunt et al, 1971). Most of the currently operating optical sensors have coarse spectral resolution - on the order of 50~200nm. As a result, such measurements are not adequate to resolve subtle variations in soil units arising due to variation in chemical composition. This has led to the development of high spectral resolution spectrometers capable of providing several spectral bands of typically 1 to 5 nanometer bandwidths.

Retrieval of soil properties in spatial scale from image spectroscopy would facilitate digital soil mapping and understanding soil processes in spatio-temporal scale. However, the transfer of relationships established at the laboratory level up to higher scales poses several problems associated with possible factors of confusion, such as (i) changes in soil roughness, moisture, illumination and view conditions; (ii) sensor characteristics like spectral and spatial resolution, radiometric calibration which may also change relationships between measured reflectance and actual soil characteristics, and (iii) possible atmospheric effects. There have been a few studies of using HRS imaging data for soil classification and parameter estimation. Most of these studies have been carried under a national-level project on hyperspectral remote sensing applications of Space Applications Centre (SAC), ISRO, and Ahmadabad. As hyperspectral imagery becomes more readily available and at lower cost, the application of partial least squares (PLS) regression to soil spectral reflectance data can provide an effective method for calculating high-resolution raster maps of important soil properties including texture, pH, and carbon and nutrient content. This information can then be used to inform farmer decision making, support precision environmental management of agricultural fields, increase sustainable crop production, and help to reduce nutrient, sediment, and carbon losses from agricultural systems.

4.1 Airborne topographic Lidar

Light Detection And Ranging (lidar) is an emerging geospatial technology that is improving our characterization of terrestrial landscapes. Advantages over other forms of remotely sensed data include spatial data collected in 3D, geo-referenced during acquisition, and ability to classify 3D elements within point clouds into user-defined surface features and above-surface features (Renslow, 2012). Improved representations of the Earth's surface, surface feature structure, and reflectance intensity allow broad use of lidar technology for mapping terrain derivatives and landscape conditions critical for soil investigations. High horizontal and vertical accuracy allow mapping of terrain features that contribute to our knowledge of soil properties and dynamic processes across multiple scales.

At a suitable resolution, lidar helps to identify subtle topographic controls on soil variability traditionally missed at coarser scales. Topography controls water redistribution on the landscape, which in turn controls pedogenesis over geologic time and subsequent soil distribution across a landscape. These scientific concepts are not new to soil resource inventories. However, data such as lidar and the other aforementioned tools provide spatially explicit representations of soils and soil processes in a quantifiable format. Digital soil mapping processes quantify and capture soil patterns determined by topography, parent materials and other soil forming factors (Jenny, 1941, McBratney et al., 2003) and this information in a digital format for computer based applications. Integration of remotely sensed data, delivery technology and conceptual scientific understanding improves soil resource management.

5. Conclusion

This paper outlines the basic principles of remote sensing based techniques for soil mapping and reviews briefly the status of current retrieval methods. There are a fairly wide variety of approaches, which have been used for soil mapping from optical, thermal infrared, passive microwave and active microwave satellite measurements. The surface features reflected on satellite image provide enough information to accurately delineate the boundaries which is accomplished effectively through systematic interpretation of satellite imageries.

As in thermal remote sensing the emitted radiations are measured, it proves to be complementary to other remote sensing data and even unique in helping to identify surface materials and features such as rock types, soil moisture, geothermal anomalies etc. The ability to record variations in infrared radiation has advantage in extending the observation of many types of phenomena in which minor temperature variations may be significant in understanding the environment.

Microwave remote sensing is the most effective technique for soil moisture estimation, with advantages for all-weather observations and solid physics. Soil moisture can be estimated using passive radiometer or active radar measurements. Both radiometer brightness temperature and radar backscattering measurements have been shown to be sensitive to soil moisture. Passive microwave has more potential for large-scale soil moisture monitoring but has a low spatial resolution. Active microwave can provide high spatial resolution but has low revisit frequency and is more sensitive to soil roughness and vegetation.

Study of physical properties, chemical properties, dielectric properties of soils with varied organic and inorganic matter is useful in agriculture to predict quality and fertility of soil. Also it is useful for the researchers working in the field of microwave remote sensing. The results from such studies are important to understand the fundamental nature of the response of particular soil to high frequency electromagnetic field.

Hyperspectral remote sensing (HRS) is emerging as a promising tool for its capability to measure the reflectance of earth surface features such as soil, water, vegetation, etc. at hundreds of contiguous and narrow wavelength bands. Availability of such a large pool of spectral information offers an opportunity to estimate multiple soil attributes from Near-Infrared (NIR), and Shortwave-Infrared (SWIR) regions (350–2500 nm) forms the basis of HRS. Chemical bonds of different molecules vibrate at characteristic frequencies when exposed to electromagnetic energy. Energy absorbed, reflected and scattered in the process may, therefore, be related to specific wavelengths. Such specificity (reflectance at characteristic wavelength) may be treated as a unique spectral feature in unique correspondence to the composition of the end-member. In particular, the specificity allows for the assessment of different soil attributes once spectral reflectance is known and a relationship between the spectral feature and soil attribute is known. Thus, spectral signatures are often considered as inherent soil properties that vary across different soils.

To utilize the HRS technology, high-resolution optical and thermal sensors are used to first create a spectral repository of reflectance spectra under controlled laboratory conditions with associated soil properties. Such spectral libraries are then used for developing spectral algorithms, for transforming processed hyperspectral signals into meaningful soil attributes.

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