



Emergent Imaging and Geospatial Technologies for Soil Investigations

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Introduction

Soil survey investigations and inventories form the scientific basis for a wide spectrum of agronomic and environmental management programs. Soil data and information help formulate resource conservation policies of federal, state, and local governments that seek to sustain our agricultural production system while enhancing environmental quality on both public and private lands. The dual challenges of increasing agricultural production and ensuring environmental integrity require electronically available soil inventory data with both spatial and attribute quality. Meeting this societal need in part depends on development and evaluation of new methods for updating and maintaining soil inventories for sophisticated applications, and implementing an effective framework to conceptualize and communicate tacit knowledge from soil scientists to numerous stakeholders.

Remotely sensed data, initially in the form of analog, unrectified panchromatic aerial photographs, became a primary soil survey technique in the early mid-20th century (Bushnell, 1932; Millar, 1932; Buckhannan, 1939). This imagery provided a synoptic view of landscapes critical for integrating soil landscape patterns with observable or measurable soil properties that can vary in both space and time. 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, orthorectification 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).

Fusion of spectra from disparate sensors with terrain derivatives from digital elevation models, soil geographic data, geostatistical predictions, and field observations provides a powerful toolset for understanding soil systems and mapping both static and dynamic properties in complex landscapes and under intensive land use practices. Recent advances in digital soil mapping (DSM) provide the framework for applying effectively advanced imaging and geospatial tools to produce input on soil properties and environmental co-variates. These data form the core of a soil inference system used to predict and map soil properties,

estimate uncertainties of spatial prediction models, and provide input to soil management programs (Boettinger et al., 2010; Grunwald et al., 2011; McBratney et al., 2003).

The next generation of imaging and telecommunications systems integrated with complex analytical methods and computing technologies will revolutionize the way we inventory and manage soil resources across a wide range of scientific disciplines and application domains (Omuto et al., 2013; Herrick et al. 2013). Papers in this special issue highlight some of those systems and methods for the direct benefit of environmental professionals and students who focus on imaging and geospatial information for improved understanding, management, and monitoring of soil resources. Five key emergent geospatial technologies not addressed in the special issue papers are profiled here: airborne topographic lidar, proximal sensing of soil properties, unmanned aerial systems (UAS), active and passive microwave sensing of soil moisture, and web-enabled soil database access, computing, and mapping.

Airborne Topographic Lidar for Characterizing Terrestrial Surface Features

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 identify subtle topographic controls on soil vari-

ability 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 package 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.

Critical to successful understanding and application of remotely sensed data is an understanding of physical architecture and soil processes that underpin observed and predicted data. Such a fundamental context empowers interpretation of remotely sensed data. The interplay of geomorphology, stratigraphy, pedology, hydrology, and vegetation determines soil geography and functions (Jenny, 1941; McBratney et al., 2003; Wysocki et al, 2012). These attributes can be evaluated in sequence from high to low positions on landscapes and expressed as soil systems (Daniels et al., 1999). Soil systems are groups of widely recurring catenas or soil sequences and constitute the architecture through which soil and ecosystem processes operate. Soil systems represent the missing link that can bridge digital information across scales. Conceptually and quantitatively they connect point

data to area data, and each soil individual to its neighbors. Soil systems, complemented by remotely sensed data, allow for up-scaling of soil and landscape dynamics to provide seamless, quantitative representations of direction, magnitude or timing of energy or materials movement within soils (or the extent to which they are retained) (Plate 1).

Proximal Sensing of Soil Properties

Proximal sensing of soil using diffuse reflectance spectroscopy (DRS) has increased our ability to estimate the spatial extent and variability of selected soil properties under diverse land management conditions. These advances have allowed the creation and expansion of digital spectral libraries and use of complex statistical models for characterizing soils, while reducing the considerable expense of traditional field-based soil investigations. Use of spectrometers to measure reflected radiation from soil samples has been demonstrated to be a lower-cost, less precise estimation alternative to direct measurements of chemical and physical properties of soils, where large numbers of observations are required to characterize an area or where the cost of field survey and laboratory analysis is high. Diffuse reflectance spectroscopy also allows for the rapid and nondestructive prediction of a wide spectrum of soil properties critical to addressing sustainable land management objectives (Bowers and Hanks, 1965; Baumgardner et al., 1985; Viscarra Rossel et al., 2010) (Plate 2).

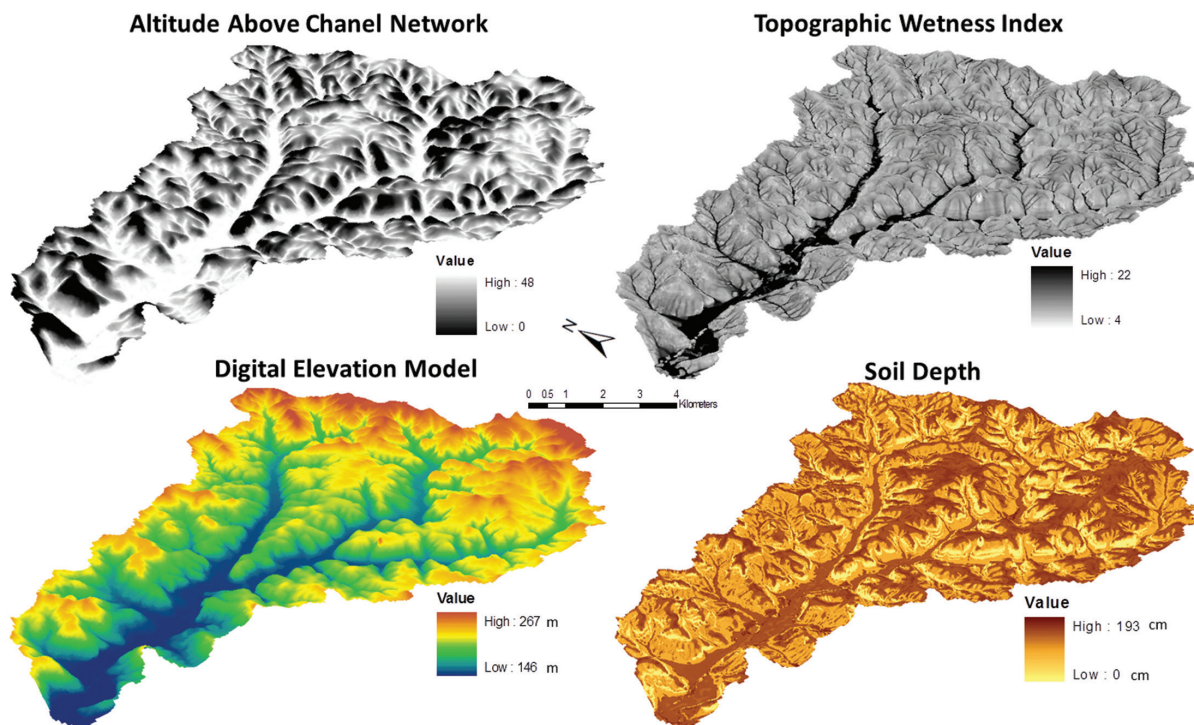


Plate 1. LIDAR derived Digital Elevation Model (DEM), terrain attributes (Altitude Above Channel Network and Topographic Wetness Index) derived from DEM and soil depth generated from the relationships between soil landscape-terrain attributes.

Unmanned Aerial Systems (UAS) for Soil Assessment, Validation, and Monitoring

Small unmanned aerial systems (sUAS), which are considered aircraft with attendant sensors that operate with no human pilot onboard, have been developed over the past few decades for both military and civilian purposes. Such systems hold considerable promise for soil scientists, given the capability of UAS to be deployed quickly and programmed to acquire imagery and geospatial data at high spatial and temporal resolutions, especially in landscapes where soil investigations occur in rugged terrain, remote regions with limited access, or pose considerable risk to field personnel (Plate 3). Current applications of sUAS focus on production agriculture to help maximize yields and reduce environmental impacts by improving nitrogen and water management and reducing nitrate leaching or nitrous oxide emissions <http://msutoday.msu.edu/news/2013/msu-lands-first-drone/>

To date, there have been limited applications of UAS to soil investigations. Such applications are focused on assessing erosion processes or mapping and modeling vegetation conditions and dynamics without explicit linkage to selected soil properties (Dandois and Ellis, 2013; Laliberte et al.,

2010; Peter et al., 2014; Rasmussen et al., 2013). Potential applications could be targeted to mapping soil patterns, mapping terrain derivatives estimated from real-time lidar-based digital elevation model, and validating boundary conditions along transects in rugged terrain (Plate 3).

Active and Passive Microwave Measurements of Global Soil Moisture

NASA is scheduled to launch the Soil Moisture Active Passive (SMAP) satellite into low Earth orbit in November 2014 (<http://smap.jpl.nasa.gov/>). The mission purpose is to provide global mapping of soil moisture and freeze-thaw state. The resulting information will aid understanding of global water, energy, and carbon cycles, advance climate science, and improve weather and agricultural yield forecasting. The satellite will carry active radar and a passive microwave radiometer to measure the backscatter and emission of microwave energy from the Earth's surface, from which global soil moisture maps will be derived. These maps will also inform water management decisions and contribute to flood and drought monitoring, among other applications of benefit to society (Brown et al., 2013; Entekhabi et al., 2010) (Plate 4).

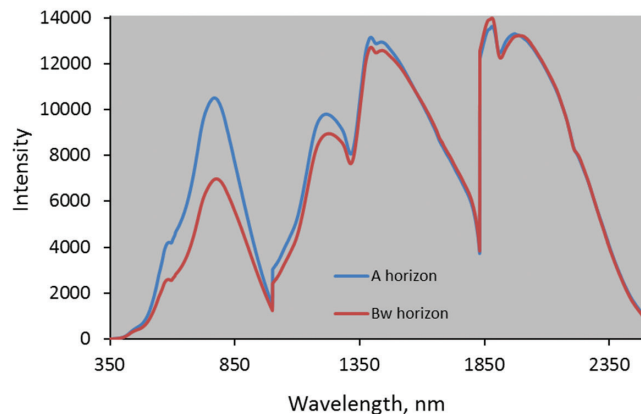


Plate 2. Soil observations and measurements using traditional visual means (upper left) and visible-near infrared diffuse reflectance spectroscopy under field and laboratory settings (upper right, lower left, respectively) with resulting spectral plot indicating reflectance properties of soil horizons, or layers.

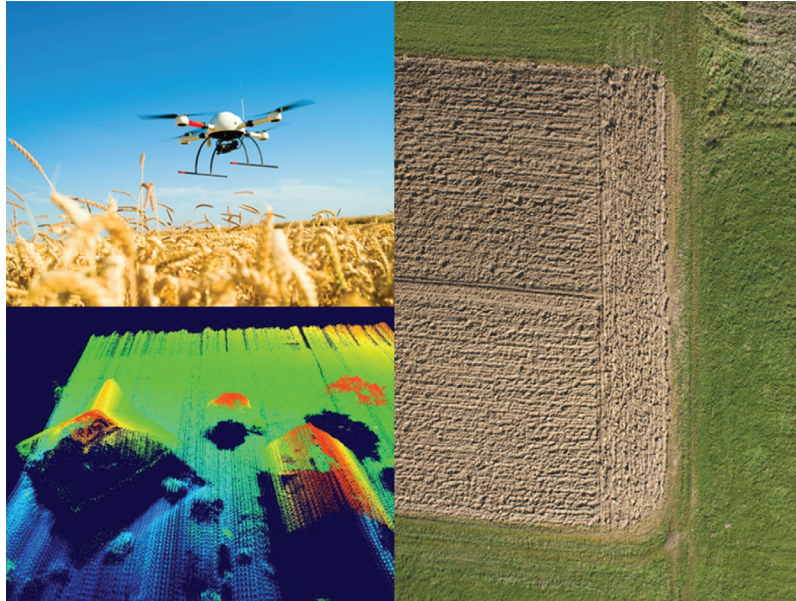


Plate 3. The small Unmanned Aerial System (sUAS) shown here has three sensors: a high-resolution radiometer; a thermal camera used to monitor plant temperature and hydration; and a laser scanner which measures individual plant height in centimeters (Images courtesy Dr. Bruno Basso, Michigan State University).

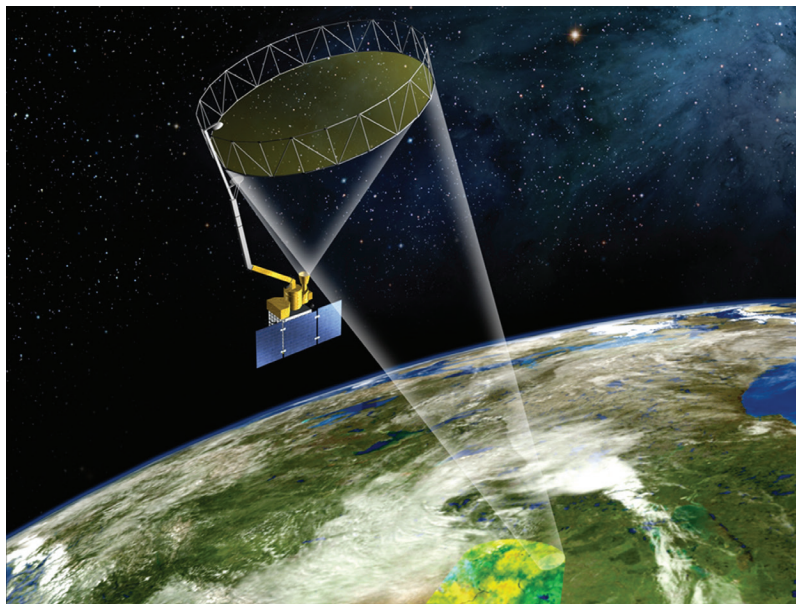


Plate 4. Artist conception of the SMAP observatory in Earth orbit. SMAP's two instruments, an L-band radiometer and an L-band radar, share a single 6-m rotating mesh reflector to produce conically-scanned data at a constant incidence angle of 40° . The SMAP configuration enables global maps of soil moisture to be obtained every 2-3 days.

Web-enabled Soil Database Access and Utilization

Soil resource inventories are some of the most complex geospatial databases in the world. Linked spatial and tabular data, one-to-many hierarchical relationships, and coding conventions can help users effectively utilize soil data to support environmental decision-making. Soil geographic data-bases are moving toward digital format and being linked to mobile de-

vices connecting individuals and communities locally and globally. This would require improved methods for accessing, analyzing and visualizing soil data and information. Advances in web-enabled technologies have stimulated the general awareness, use, and visualization of soil properties readily available in sophisticated soil geographic databases (Soil Survey Staff, 2014). In order to accommodate the widest possible spectrum of potential soil data users, flexible interfaces to these resources (web-based APIs, web-mapping clients, data-streams, etc.)



Plate 5. US SoilWeb, enabled using mobile phone apps, allows for wide utilization of soil data in the field by scientists and practitioners.

on a variety of platforms (desktop computers, tablet devices, smartphones, etc.) are needed (Beaudette and O'Geen, 2010; Beaudette and O'Geen, 2009). Application of these technologies is critical for agronomic and environmental assessments in rural and urban areas from local to global scales. (Plate 5).

Summary

We encourage our community to advance understanding of these important imaging and geospatial technologies for soil investigations. We need to strengthen educational, outreach, and professional certification programs to ensure informed and ethical applications of emergent sensor capabilities and knowledge-based systems. Lastly, we must serve as effective advocates of advanced sensor development, standardized processing and modeling of soil data and environmental co-variables, and appropriate integration of soil information for effective assessment and monitoring of environmental impacts and societal decision making.

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