ENVIRONMENTAL SCIENCE

Digital Soil Map of the World

Increased demand and advanced techniques could lead to more refined mapping and management of soils.

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Soils are increasingly recognized as major contributors to ecosystem services such as food production and climate regulation (*1*, *2*), and demand for up-to-date and relevant soil information is soaring. But communicating such information among diverse audiences remains challenging because of inconsistent use of technical jargon, and outdated, imprecise methods. Also, spatial resolutions of soil maps for most parts of the world are too low to help with practical land management. While other earth sciences (e.g., climatology, geology) have become more quantitative and have taken advantage of the digital revolution, conventional soil mapping delineates space mostly according to qualitative criteria and renders maps using a series of polygons, which limits its resolution. These maps do not adequately express the complexity of soils across a landscape in an easily understandable way.

The Food and Agriculture Organization (FAO) of the United Nations (UN) and the UN Educational, Scientific and Cultural Organization (UNESCO) published the first world soil map in 1981, using a single soil classification terminology (*3*). The map has been utilized in many global studies on climate change, food production, and land degradation. But its low resolution (1:5 million scale) is not suitable for land management decisions at field or catchment scales. One of the most-cited soil degradation studies, the *Global Assessment of Human Induced Soil Degradation*, is based on expert judgment by a few individuals, has very low resolution (1:50 million scale), and lacks quantitative information on soil properties that indicate the degree of soil degradation (*4*). At present, 109 countries have conventional soil maps at a scale of 1:1 million or finer, but they cover only 31% of the Earth's ice-free land surface, leaving the remaining countries reliant on the FAO-UNESCO map (*5*). [See supporting online material (SOM) for more history.]

To address these many shortcomings, soil scientists should produce a fine-resolution, three-dimensional grid of the functional properties of soils relevant to users. We call for development of a freely accessible, Web-based digital soil map of the world that will make georeferenced soil information readily available for land-users, scientists, and policy-makers. A foundation for such an effort is being laid by the GlobalSoilMap.net (GSM) project. This effort originated in 2006 (*6*) in response to policy-makers' frustrations at being unable to get quantitative answers to questions such as: How much carbon is sequestered or emitted by soils in a particular region? What is its impact on biomass production and human health? How do such estimates change over time?

The GSM consortium's overall approach consists of three main components: digital soil mapping, soil management recommendations, and serving the end users—all of them backed by a robust cyberinfrastructure. [See fig. S1, expanded from (*7*).] Specific countries may add their own modifications.

Maps can provide soil inputs (e.g., texture, organic carbon, and soil-depth parameters) to models predicting land-cover changes in response to global climatic and human disturbances.

Digital Soil Mapping

Digital soil mapping began in the 1970s (*8*) and accelerated significantly in the 1980s because of advances in information and remote-sensing technologies, computing, statistics and modeling, spatial information and global positioning systems, measurement systems (such as infrared spectroscopy), and in more recent times, online access to information. Experimentation with these technologies is leading toward consensus (*7*, *9*–*12*), and operational systems are being implemented.

A digital soil map is essentially a spatial database of soil properties, based on a statistical sample of landscapes. Field sampling is used to determine spatial distribution of soil properties, which are mostly measured in the laboratory. These data are then used to predict soil properties in areas not sampled. Digital soil maps describe the uncertainties associated with such predictions and, when based on time-series data, provide information on dynamic soil properties. They also differ from conventional, polygon-based maps, in that they are pixel-based and can be more easily displayed at higher resolutions currently used by other earth and social sciences.

There are three main steps in digital soil mapping. Step 1, data input, starts with the production of base maps, assembling and calibrating spatially contiguous covariates from available data [e.g., the 90- × 90-m resolution digital terrain models from Shuttle Radar Topography Mission (SRTM v.3)]. Covariates, reflecting state factors of soil forma-

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tion (*13–15*), include climate information (e.g., temperature, rainfall, evaporation); land cover (e.g., Normalized Difference Vegetation Index); a range of digital terrain variables; and geological variables relating to soil parent materials (e.g., airborne gamma radiometric spectroscopy).

In developed countries, there may be sufficient point soil observations to allow putting a fraction aside to subsequently test and cross-validate the map for "ground truth." In Africa, ground-truthing has been built into the system. Over the next 4 years, experimental sites will be established in 60 sentinel landscapes, which have been randomized across an 18.1 million km^2 of sub-Saharan Africa.

Collection of legacy soils data (preexisting, georeferenced field or laboratory measurements) is an important part of step 1. Major investment in new soil measurement will be required in countries having sparse soil legacy data.

Step 2 involves estimation of soil properties, expressed as probabilities of occurrence (*16*). They are derived by using quantitative relations between point soil measurements and the spatially continuous covariates. This results in maps of soil properties, such as the ones selected by the GSM consortium as the minimum data set—clay content, organic carbon content, pH, estimated cation-exchange capacity, electrical conductivity, and bulk density (to convert carbon and nutrients on a mass basis to a land-surface-area basis for biogeochemical modeling). This process enables production of maps that use a range of soil classification systems.

In step 3, spatially inferred soil properties are used to predict more difficult-to-measure soil functions, such as available soil water storage, carbon density, and phosphorus fixation. This is achieved using pedotransfer functions (*11*), including those in the Fertility Capability Classification system (*17*, *18*), such as aluminum toxicity, or those included in environmental models (*15*). These soil functions largely determine the capacity of soils to deliver various provisioning and regulating ecosystem services. The overall uncertainty of the prediction is assessed by combining uncertainties of input data, spatial inference, and soil functions.

Soil Management Recommendations

After the three-step soil-mapping process, data from reliable, georeferenced field trials are compiled in step 4. This step is analogous to the data capture of step 1, except that the covariates in this case are "social": digital maps of land use, agroecological zones, farming systems, crop yields, poverty, road density, and input supply networks, as well as crop models, such as those being assembled by HarvestChoice (*19*). These social covariates address additional state factors of soil formation: organisms (other than vegetation), time, and human activities (*13*, *14*). Legacy data from field trials are used to develop models and transfer functions for specific soil management recommendations. (See SOM for further information.)

Serving the End Users

Step 5 is to develop evidence-based soil management recommendations. This relies on analysis of soil functions of step 3 and the legacy data, social covariates, and new experimental data obtained in step 4. Resulting maps and management recommendations form a baseline against which changes can be monitored and evaluated over time. Principal user groups are typically agricultural extension workers and policy-makers whose main task is to reverse soil degradation, to preserve and maintain soil health, and to improve food security and household livelihoods. Other users include research and modeling communities, farmer associations, environmental extension services, agribusinesses, and nongovernmental and civil society organizations. The cyber-infrastructure should encourage feedback, with appropriate quality standards developed for the incorporation of such information.

Products will be tailored to specific needs of end users. For commercial farmers and national planners, the basic 90-m resolution is appropriate (roughly equivalent to 1:90,000 scale). The basic product for smallholder farmers might be at 30-m resolution. For some research, for example, studies of nutrient cycling, resolution may need to be finer, whereas for a study of global fertilizer policy a 1-km resolution may suffice.

Effective irrigation is another application requiring high-quality soil information. For example, in order to alleviate droughts in the central North China Plain, more water is often pumped into fields than the soil can hold. In the long run, irrigation must be tuned to local soil conditions (e.g., profile water storage and permeability) to alleviate water scarcity.

Developments in geographic information systems, online services, and mobile technologies are providing new ways to build, leverage, and disseminate spatial information. The intergovernmental Group on Earth Observations (GEO) is building the cyberinfrastructure needed to link numerous emerging systems for monitoring and predicting global environmental change. GEO is orchestrating these efforts through the Global Earth Observation System of Systems (GEOSS), a network of content providers intended to support a wide variety of end users (*20*). Digital soil information is likely to be welcomed by such groups. For example, GSM will focus on providing soil inputs (e.g., texture, organic carbon, and soil-depth parameters) to Soil-Vegetation-Atmosphere Transfer models that are used to predict land-cover changes in response to anticipated climatic and human disturbances across the globe.

A new generation of soil scientists must be trained in this approach. The resultant new maps and management recommendations will help address some of the main challenges of our time: food security, climate change, environmental degradation, water scarcity, and threatened biodiversity.

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Supporting Online Material

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