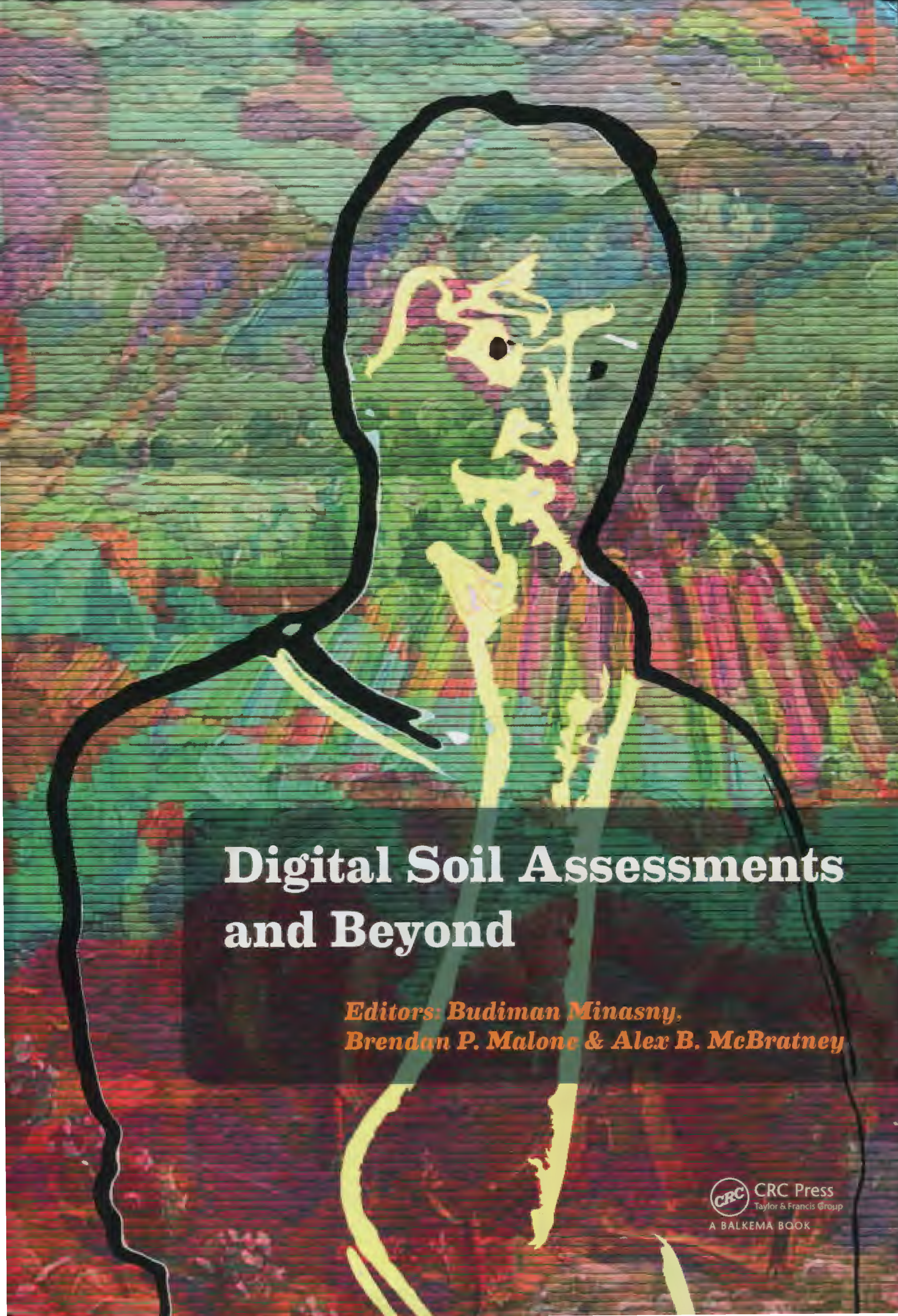

Digital Soil Assessments and Beyond

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Digital Soil Mapping in a changing world

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ABSTRACT: In the Anthropocene, processes and response feedbacks to soil-ecosystems have accelerated, jeopardizing the sustainability of the soil resource at local, regional, national, and global scales. Soil-ecosystems are at the heart of the critical zone and sustain life on Earth by providing a quasi non-renewable resource that, once degraded, is extremely slow to restore. Yet global change, such as population growth, climate change, and drastically altered land use, imposes profound imprints onto soil-ecosystems impacting soil quality, biodiversity, and food security. Questions emerge about the role of digital soil mapping (DSM) in the context of a changing world. Implementations of contemporary digital soil models have emphasized mapping of soil-forming or SCORPAN factors assuming that they are more or less static to infer on soil properties or classes. This perspective is constraining and does not capture soil evolution, i.e., the change of soil properties and their environmental covariates through time. We have proposed to enhance conceptual soil models to explicitly incorporate the soil-ecosystem evolution and anthropogenic forcings into the modeling process. Our space-time modeling framework, called STEP-AWBH ("step-up"), consists of soil (S), topographic (T), ecological (E), geologic (P), atmospheric (A), water (W), and biotic properties (B) as well as human-induced forcings (H) to predict pixel-based soil properties or behavior. We discuss how contemporary DSM can be expanded to enhance capabilities to respond to grand challenges we face at global scale linked to sustainability, vulnerability, adaptability, and risk assessments of soil-ecosystems across multiple spatial and temporal scales.

1 INRODUCTION

1.1 *A changing world*

Profound shifts have occurred during the last three centuries in which human activities have become the main driver of global environmental change. In this new epoch, the Anthropocene, human-driven changes, such as population growth and drastically altered land use, are pushing the Earth system well outside of its previous operating range, causing severe and abrupt impact on soils and ecosystems (Crutzen, 2002). Global climate change and other natural and human-induced forcings, provide new challenges to assess the effects on soil resources that provide profoundly important ecosystem services. In the Anthropocene, ecosystem processes and response feedbacks to ecosystems have accelerated jeopardizing the sustainability of the soil resource at local, regional, national, and global scales. These issues are exacerbated by the fact that environmental, social, cultural, political, financial, and economic systems have become globally interconnected to a degree where change or collapse of one component impacts the global system as a whole. Deep understanding of causative links and mechanistic processes in the space, time, and human dimensions is needed to describe the nexus of coupled systems, including human-environment, soil-crop, soil-yield, soil-water, and other coupled systems in a changing world.

Unacceptably large uncertainties remain in regional and global soil assessment and modeling posing risks and threats to maintain soil, food, bio-, energy, water, and environmental security. Although efforts are underway to create global soil maps at striking spatial resolution (100 m) through the Global Soil Map.net initiative these maps will only provide snapshots of historic soil conditions. Most available soil information systems are archives from the past with a wealth of legacy data representing historic ecosystem conditions. New challenges are eminent in a rapidly changing world, for instance, to improve back—and forecasting of soil patterns and evolution. To perceive a digital representation of soils as the ultimate goal of digital soil mapping (DSM) may be too simplistic. Efforts to tie DSM to soil risk assessment, ecosystem services, soil security, and sustainability of soil-ecosystems (Foley et al., 2011) are critical to be embedded into a integral, global change framework. A new generation of DSM is needed that explicitly consider scaling behavior across space and time, improve linkages between the biophysicochemical and human domains, and assess adaptability, vulnerability, sensitivity, and risk to soilscapes under a plethora of imposed change.

1.2 *Interactions between a Changing World and Soils*

The evolution of soils is tightly connected to the internal and external changes imposed onto them. Soils represent memory banks that record the history of natural and human impacts and the sensitivity of soil attributes differs widely from fast response (indicator variables) to slow response variables that take hundreds of years to change. As Richter et al. (2011) pointed out, we know far too little about the rates of soil change in response to land management, about soil resilience to historic and contemporary management, and about soil response rates to improved land management and changes in climates.

A new, adapted vision to DSM is needed that embraces human-induced changes imposed on soils and soil evolution. This future DSM paradigm goes beyond production of 'static' soil representations in form of points, polygons or grids (maps). This paper provides a brief overview of contemporary philosophical worldviews to model soilscapes, limitations and constraints of state-of-the-art DSM, and presents a vision for DSM explicitly integrating space, time, and human dimensions into the modeling process.

2. TREATISE: PHILOSOPHICAL WORLDVIEWS TO MAP SOILSCAPES

Digital soil mapping has made major contributions to move conceptual soil models into the digital world and quantify soil attributes (and somewhat soil processes). According to Churchman (2010), who outlined the philosophical status of soil science, three major views of soils exist: (i) the formation and properties of horizons that represent the integrated effects of a range of environmental factors upon geological materials; (ii) the occurrence and properties of aggregates that represent a range of strengths and duration of inter-particle associations; and (iii) the occurrence and behavior of heterogeneous colloidal materials. Contrasting philosophical worldviews have been employed to describe and characterize soilscapes including (i) empiricism, (ii) metaphysics, (iii) epistemology, (iv) reductionism, (v) determinism, (vi) holism, and (vii) pragmatism.

Empiricism focuses on measurements and observations of soil properties and processes at micro, site-specific, field or coarser spatial scales across a variety of temporal scales. These empirical data are profoundly important to describe soilscapes feeding into digital soil models. A major constraint for continental and global DSM has been the lack in harmonizing historic soil data and establishment of soil monitoring networks that consistently track soil evolution through time.

Metaphysics (Loux, 2002) is concerned with explaining the fundamental nature of being and the world including soilscapes and soil-landscapes. Typical metaphysical questions posed are "What is there?" and "What is it like?". Here the notion of space-time, cause-effect, and possibility of change in soils and its properties is critical to understand its behavior. Rooted in metaphysics are ontologies and conceptual models that formalize thinking about soils, interactions between soils and the environment and humans, and external and internal forcings. Examples include factorial models such a CLORPT (Jenny, 1941) and SCORPAN (McBratney et al., 2003) that aim to map and explain soils (properties or classes) at a specific time ignoring somewhat trajectories of change in soils and associated environmental covariates. The explicit incorporation of human-induced impacts on soil genesis is often only indirectly addressed in these contemporary digital soil maps (e.g., considering land use/land cover at a specific time without considering the impact of land use change on soil development through time). Although metaphysics is a type of philosophy focused on broad concepts to describe reality and our understanding of it (i.e., "things or soils we think we can measure or observe"), it also concerns explaining the features of reality that exist beyond our immediate senses, including projecting our understanding of soilscapes into the future. Unexplained variance is inherent in digital soil models and explaining random errors or model noise may be perceived as a matter of metaphysics.

Epistemology, the theory of knowledge, is a branch of philosophy that investigates the origin, nature, methods, and limits of knowledge. Notably, there is a distinction between epistemology that emphasizes "knowing *that*" over "knowing *how*" (a process or method) central to other worldviews. As such, the epistemological view of soils focuses on mapping spatial (or temporal) patterns of soil attributes (e.g., soil organic carbon) aiming to know the truth (i.e., accurate quantification) or belief (i.e., estimate soil properties through a model). Since we are unable to measure all soil properties and processes at all locations and through time digital maps of soils—assuming measurements provide us with the "truth about soils"—are bound somewhat to beliefs. This is specifically the case in classical polygon-based soil maps that aggregate soil variability within units, but also gridded soil maps that assume the pixel contains the "truth" about physico-chemical or biological soil conditions (compare Grunwald et al., 2011). These assertions become more critical as we apply DSM to continental and global scales where our belief and models are put to test. Epistemology asserts on criteria by which we can judge the reliability of knowledge-claims. Applied to the DSM context, it focuses on error and uncertainty assessment, and verifications to estimate/simulate soil properties or processes constraining soil assessment.

Reductionism aims to reduce the whole (e.g., soilscapes or soils) to its individual constituents (e.g., horizons, attributes, aggregates, and colloids) assuming that the sum of its parts = the whole. In the DSM context reductionism has been applied to produce high spatial resolution soil maps using exhaustive sensor-measurements typically constraint to fine spatial scale, which require recalibration when applied elsewhere. Reductionism posits to transfer laws/models based on physical understanding to other locations or upscale results to coarser landscape scales. Due to the non-linear, complex, and sometimes chaotic behavior of soil-environmental interactions the reductionist viewpoint imposes constraints, because in reality controlling soil-forming factors differ from site-to-site, and across spatial and temporal scales. Thus, to build a generalized, universal digital model that quantifies spatial and temporal patterns of soils across the globe adopting a reductionist worldview seems out of reach in the near future.

Determinism and reductionism are often interconnected because both strongly reflect a certain perspective on causality and the ability to understand phenomena or soil forming processes completely. Determinism is at the conjunction between measuring (e.g., carbon flux) and describing physico-chemical and biological processes in soils through laws, algorithms or mechanistic models (e.g., Century model). Purely mechanistic soil process models are still rare and often intermixed with empirical components. However, deterministic models have the ability to model soil change under imposed natural and human-induced stressors, such as land use and global climate change.

Holistic perspectives examine emergent properties of complex systems that are considered irreducible and posit that the individual parts are larger than the whole. Holism asserts that natural systems (physical, biological, chemical, social, economic, mental, etc.) and their properties should be viewed as wholes, not as collections of parts. This perspective argues that systems somehow function as wholes and that their functioning cannot be fully understood solely in terms of their component parts. Holarchies are rooted in the concept of holons (Greek *holos* "whole") regarded as either a whole or a part, depending on the perspective (Wilber, 2000). Holism is inherent in digital soil maps where soil map units (polygons or grids), horizons, or layers are assumed internally homogeneous and in some applications aggregated to larger geographic units (e.g., polypedons or catenas). To assess soil sustainability, vulnerability and adaptability to imposed changes (e.g., global climate change, economic—or policy induced changes of agro-forest systems), require a multidimensional perspective to integrate soil, environmental, human, and other factors along with fluxes between model components into more complex models (Peters et al., 2008). Integration of contemporary digital soil maps bundled into larger frameworks to address impacts in a changing world have not been fully materialized yet.

Pragmatism, a movement of American origin, is a method for solving or evaluating intellectual problems and asserts that a theory or model is true if it works. In context of DSM, pedo-transfer functions build on inferential modeling of cheap to measures soil attributes from more difficult to measure attributes, meta-analysis, data mining (e.g., ensemble regression trees to predict soil carbon), and others may be considered pragmatic in their approach. Pragmatism has spanned off applications in which digital soil maps are utilized or combined with other environmental or socio-economic data to evaluate soil conditions, degradation or use potential (e.g., ecosystem service assessment).

3 FUTURE DIGITAL SOIL MODELING

Future adaptive DSM is bound considering the following dynamics: (i) The world is becoming increasingly connected through accelerated flows of material and information, both within and among soilscapes and regions that may or may not be adjacent or even close to each other; (ii) Connectivity pathways allow fine-scale processes to propagate and impact large areas; and

$$SA(z, p_x, t_c) = f\{\sum_{j}^{n} S_j(z, p_x, t_c), T_j(p_x, t_c), E_j(p_x, t_c), P_j(p_x, t_c)\}; \int_{i=0}^{m} \{\sum_{j}^{n} A_j(p_x, t_i), W_j(p_x, t_i), B_j(p_x, t_i), H_j(p_x, t_i)\}$$

SA:	Target soil property (e.g., soil organic carbon or soil carbon sequestration rate)
S:	Ancillary soil properties (e.g., soil texture, soil spectral data)
T:	Topographic properties (e.g., elevation, slope, curvature, compound topographic index)
E:	Ecological / geographic properties (e.g., physiographic region, ecoregion)
P:	Parent material; geologic properties (e.g., geologic formation)
A:	Atmospheric properties (e.g., precipitation, temperature, solar radiation)
W:	Water properties (e.g., surface runoff, infiltration rate)
B:	Biotic properties (e.g., vegetation/land cover, land use, land use change, spectral indices derived from remote sensing, organisms)
H:	Human-induced forcings (e.g., contamination, greenhouse gas emissions - GHG) [Note: the H factor includes human activities that force the change, such as GHG, which may alter other factors. For example, global climate change is the result of feedbacks of anthropogenic and natural forcings and processes. The actual change in climate is represented by A]
j:	Number of properties from j = 1, 2, ….., n
p_x:	Pixel (p) with size x (width = length = x) at a specific location on Earth
t_c:	Current (c) time (t)
t_i:	Time to current (t_c) with time steps i = 0, 1, 2, …., m
z:	Depth

Figure 1. STEP-AWBH model.

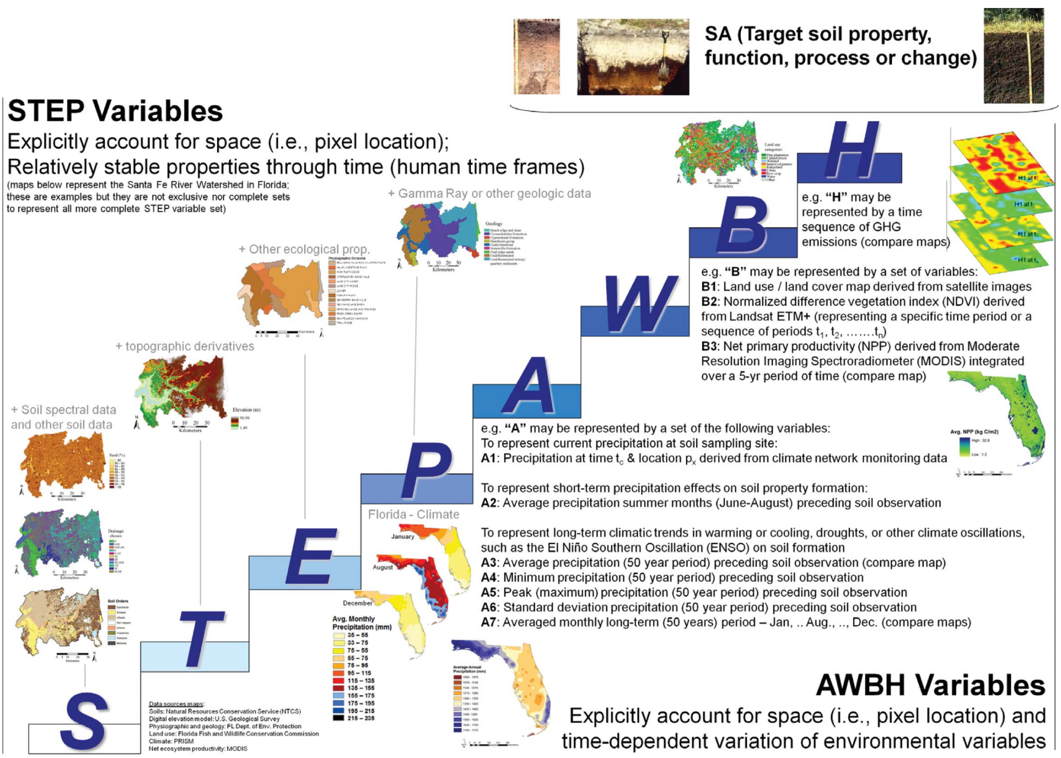

Figure 2. Examples how to populate the STEP-AWBH model.

in some cases, broad-scale drivers can overwhelm fine-scale processes to alter soil-ecosystem dynamics demonstrating often non-linear dynamics and thresholds that can flip a system into a different state; and (iii) Changes in connectivity have the potential to produce rapid and dramatic changes in soil-ecosystem dynamics unlike any observed in recorded history (adapted from Peters et al., 2008). Spatial and temporal cross-scale interactions of soil-ecosystems in a world undergoing accelerated change in soil-forming (external) and internal (soils) factors are extremely complex.

The proposed conceptual DSM model called STEP-AWBH (Fig. 1) (Grunwald et al., 2011) explicitly accounts for anthropogenic and natural forcings which determine and modulate soils and space-time interactions. The STEP-AWBH (phonetically, "step-up") model is spatially and temporally explicit where the soil property of interest, SA, is estimated from various spatially explicit environmental variables (STEP) that tend to be static within a human time frame, and thus, is represented in the model at one specific time (t_c or, if available, t_i). The AWBH factors explicitly account for space (i.e., pixel location) and time, whereby the time component may be aggregated to represent different time vectors or represented for different time periods in the model. Here it is critical to note that temporal change in AWBH factors is represented in the model that correlate with soil change. For example, land use change (e.g., derived from satellite data), climate change (e.g., mean annual change in temperature over past 100 years or monthly precipitation over a 50 year period), or change in phenology (e.g., peak and amplitude Normalized Difference Vegetation Index aggregated over past 10 years) may be incorporated in Eq. (1). Other examples are found in Fig. 2. The H factor represents different anthropogenic forcings that can act over shorter or longer periods of time on SA (z, p_x, t_c) to shift SA into a different state, such as greenhouse gas emissions, contamination (e.g., oil spill), disturbances, overgrazing, etc. The conceptual soil evolution model can be implemented using mixed stochastic/deterministic methods (e.g., regression trees, ensemble trees such as Random Forest, regression kriging, or mechanistic simulation models). Depending on the geographic setting and history of a soil-landscape, one (or more) of the factors in EQ. (1) impart(s) major control on SA, which may shift into a different state due to scaling up of models to coarser landscape scales, crossing geographic or attribute domain boundaries, or disproportional impact of anthropogenic forcings. The STEP-AWBH model can be adapted to forecast and hindcast soil properties. STEP-AWBH provides a framework to capture soil evolution, i.e., the change of soil properties and their environmental covariates through time.

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