Part I – Conceptualization of a Meta Soil Model

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ABSTRACT: To address global issues, such as adaptation to climate change, land use changes of unforeseen dimensions, food security, and global sustainability concerted efforts are needed to build the next generation of digital soil maps/models. Globally, changes in societies, the environment, and soils have accelerated in the Anthropocene and we are challenged to produce multiple new digital soil products that capture those changes. This paper introduces the Meta Soil Model (MSM) that is juxtaposed to formalize digital soil mapping (DSM) disclosing a 'multiple soil object' that is revealed through different perspectives/philosophical worldviews including axiology [values] (*the Why*), motivations, needs, and purposes (*for What/Whom*), ontology (*the What*) and hermeneutics (interpretation), epistemology (*the Who*), and methodology (*the How*). The broad spectrum MSM theory facilitates to make DSM integration pathways more transparent to prioritize/select those that are "better in some way" than others and allows intra- and intercomparisons of different DSM integration pathways.

1 INTRODUCTION

1.1 *Rationale and Significance*

In the U.S., the Natural Resources Conservation Service provides publicly available soil data, which includes the National Cooperative Soil Survey Characterization (Pedon) Data, Soil Survey Geographic Database (SSURGO), and the U.S. General Soil Map (STATSGO2). Various U.S. soil maps have been produced using polygon-based map units and soil attributes and taxonomic classes across various map scales, with the finest at 1:24,000 (SSURGO). Few map products using simple spatially weighted means calculations according to specifications of the Global Soil Map (GSM) have been generated. Recently, a gridded version (gSSUGRO) was released at 10 m spatial resolution which is based on the same legacy soil data and same underlying SSURGO data. These products are extraordinary in terms of coverage and soil information they provide; but they are just one realization of national soil attribute maps that serve global soil assessment. Grunwald et al. (2011) asserted that the need for up-to-date, high-quality, high-resolution, spatiotemporal, and continuous soil and environmental data that characterize the physicochemical, biological, and hydrologic conditions of ecosystems across continents has intensified. To address global issues, such as mitigation and adaptation to global climate change, land use and biome changes of unforeseen dimensions, food security and planetary sustainability concerted efforts are needed to build the next generation of digital soil maps and models. Globally, changes in societies, the environment, and soils have accelerated in the Anthropocene (Richter et al., 2011) and we are challenged to produce multiple new digital soil products that reflect those changes.

1.2 *Goals*

In this paper a conceptual theory for a 'Meta Soil Model' (MSM) is presented that incorporates historic and contemporary soil and environmental datasets to enable production of various realizations of soil attributes and more complex soil ecosystem assessments, such as risk, vulnerability, adaptability, and sustainability. The MSM describes soil evolution in space and time and includes the human dimension not as an external driving force to soil formation, but as a co-creator of soil-ecosystems that are undergoing continuous change.

How knowledge and understanding of soils is formed plays a central role and covers a wide spectrum of intrinsic and extrinsic motivational principles. Intrinsic knowledge building is focused to create soil maps "just for the sake of them, because we have the technical knowledge to do so" (e.g., researcher's perspective) or "because there is a mandate to produce them" (e.g., governmental perspective). In contrast, extrinsic knowledge formation is motivated to address complex societal global issues in a rapidly changing world where preservation of sustainable soil resources is threatened by an increasing world population and needs for various soil ecosystem services. From this perspective human needs are viewed as the motivational force to co-create soil-ecosystems whereby digital soil maps and models are the media to facilitate the process. These underlying intrinsic and extrinsic goals to produce digital soil products are distinctly different and often reduced to the perspective that "one soil map does it all", i.e., has the capacity to accommodate various purposes, needs, spatial and temporal scales, audiences, and stakeholders. For example, the GSM has the mission to produce various gridded (100 m resolution) soil property maps according to specifications at global scale.

Given the multiplicity of geographic soil differences with profound disparities in ecosystem change at global scale the need for complimentary digital soil mapping (DSM) approaches arise. The MSM is a first step in this direction providing a formalized approach to create digital soil realizations grounded in various philosophical worldviews including axiology (*the Why*), motivations, needs, and purposes (*for What/Whom*), ontology (*the What*) and hermeneutics (interpretation), epistemology (*the Who*), and methodology (*the How*) (Figure 1).

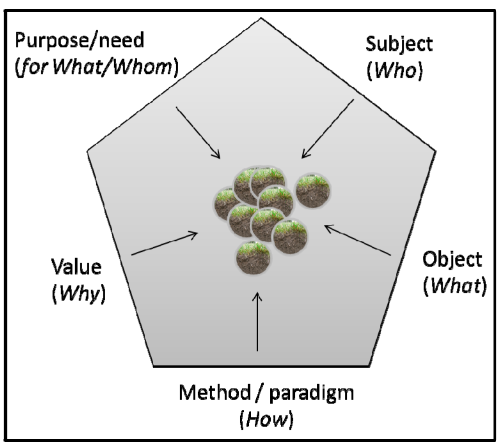

Figure 1. The dimensions of the Meta Soil Model that define the 'multiple soil object' disclosed by different perspectives/worldviews.

2 APPROACH

2.1 *Essence of the Meta Soil-Model*

The contemporary DSM paradigm views soils as objects (or phenomena) to be mapped. A paradigm is defined as a worldview underlying the theories and methodology of a particular scientific subject. Other paradigms view soils as valuable resource to be preserved (sustainability paradigms rooted in environmental ethics) (Kidd, 1992), natural capital that brings benefits to humans (ecology oriented paradigms applied in context of ecosystem services assessment) (Costanza, 2003), human co-created ecosystems (autopoiesis; and social science paradigm) (Moeller, 2006) or embodiment of Earth (spiritual paradigms) (Wilber, 2000). The trend in DSM to quantify soils at finer and finer scales will not necessarily bring forth new knowledge and understanding of soils. On the contrary, in a fast changing global world that is complexifying in terms of emerging patterns and relationships the integration of knowledge and synthesis cutting across and infusing different disciplines have become profoundly important (Eigenbrode et al., 2007; Bammer, 2013). DSM is poised to play a major role in such inter- and transdisciplinary approaches featuring synthesis and integration adopting multiple paradigms to view soils.

Uniting epistemological distance (the *Who*), methodological variety (the *How*), and ontological complexity (the *What*) in context of axiology (values associated with soils), purposes, and needs disclose a multiple object (i.e., not only one soil but many soils viewed from different perspectives/worldviews), because every perspective reveals multiple enacted objects or 'multiple soil objects' (Figure 1). This assertion is in analogy to the 'multiple object global climate change' outlined by Esbjörn-Hargens (2010) that arises based on different perspectives (e.g., individuals, groups, and observer(s) perspectives), ontological description of the global climate change phenomena, and methodologies used to describe it ranging from measurements, global climate change circulation models, to phenomenological descriptions based on direct experience. The 'multiple soil object' is disclosed by a MSM that offers the flexibility to use different DSM methodologies to infer on multiple soil objects (e.g., properties, classes) or phenomena (e.g., ecosystem services, gaps, ……, sustainability) based on needs and values of users and stakeholders (Figure 2). Thus, it offers the flexibility to view soils as realizations of different perspectives or worldviews.

In its core the MSM is perceived as a meta-perspectival, meta-methodological, meta-paradigmatic, and ontologically informed process combining soil- and environmental data to create soil models for the purpose of knowledge formation (e.g., describe soil carbon patterns and distributions) and meaning making (e.g., assess the vulnerability of soil carbon loss to climate change). The latter is focused on understanding of patterns and relationships of soil-ecosystems, their adaptability, vulnerability, sustainability, and sensitivity in response to natural and human-induced change that co-create systems.

Importantly, humans are viewed not only as an external forcing that imposes change onto soil-ecosystems (Cornell and Parker, 2010) (e.g., through management and use of soils for agricultural

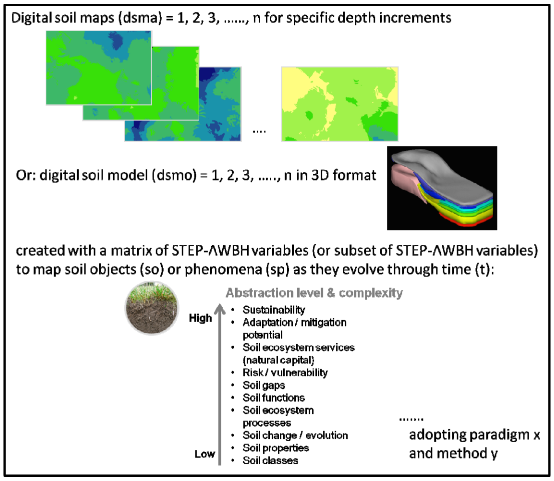

Figure 2. Overview to apply the Meta Soil Model to map or model soils.

production or global climate change) where humans are coupled to the environment like economic or social systems. Cornell (2010) eloquently pointed out that it is now slowly being recognized that socio-ecological systems interact and are interdependent where humans are considered to act as agents co-creating their environment. The autopoietic paradigm has the potential to add a new dimension to traditional soil mapping approaches.

The MSM conceptually offers flexibility to adapt to multiple paradigms and create a variety of soil realizations. The term soil realization acknowledges that there is not only one soil map that represents the soil continuum, but several possible ones that approximate reality. In that sense they honor the worldview of a 'multiple soil object'. *Meta* ("after", "beyond", "self") is used to indicate a concept that is an abstraction from another concept. The MSM is pluralistic because it includes not only one map for one soil attribute, but entails a wide array of different soil assessments enabled by a pluralistic perspective including multiple data that represent the total soil-ecosystem and methods and paradigms. Each method/approach has its own verification/validation process to be included in a MSM. The multiplicity of soil models created with different approaches, paradigms and underlying perspectives facilitates to form ensembles and integrated bundles of models that allow convergence approximating soil reality.

2.2 *Formalization of the Meta Soil-Model*

To formalize the MSM the following components are critical: (1) soil-ecosystem ontology (i.e., selection and harmonization of soil and environmental data that represent the total ecosystem in space and time), (2) methods applied to predict/simulate soil properties, processes, and abstract soil concepts (such as risk, sustainability, soil carbon gap) focused on integration of epistemic knowledge and understanding of soil-ecosystems, and (3) identification of the purpose, intent and/or motivation that is guided by values and beliefs (e.g., in a specific paradigm or worldview) of DSM experts producing soil realizations and those who need them.

(1) Soil-ecosystem ontology: Soil and environmental covariates are collected, assembled, and mined to provide an exhaustive data set to accommodate inference on the 'multiple soil object' using a variety of known paradigms and methodologies. The STEP-AWBH model allows to populate the total soil-ecosystem and its evolution as outlined by (Grunwald et al., 2011).

$$\mathrm{SA}(z, p_x, t_c) = f\left\{\sum_j^n \left[S_j(z, p_x, t_c), T_j(p_x, t_c), E_j(p_x, t_c), P_j(p_x, t_c)\right]\right\}; \int_{i=0}^{m} \left\{\sum_j^n \left[A_j(p_x, t_i), W_j(p_x, t_i), B_j(p_x, t_i), H_j(p_x, t_i)\right]\right\} \quad (1)$$

where, SA is the target soil realization, S represents ancillary soil properties, T represents topographic properties (e.g., elevation, slope, compound topographic index), E represents ecological properties (e.g., physiographic region, ecoregion), P represents the parent material and geologic properties (e.g., geologic formation), A represents atmospheric properties (e.g., precipitation, temperature, solar radiation), W represents water properties (e.g., soil moisture, surface runoff), B represents biotic properties (e.g., vegetation or land cover, spectral indices derived from remote sensing, organisms), and H is human-induced forcings (e.g., land use and land use change, contamination, disturbances). j is the number of predictors, j = 1, 2, …, n, p_x is a pixel with size x (width = length = x) at a specific location on Earth, t_c is the current time, t_i is the time to t_c with time steps i = 0, 1, 2, …, m, and z is soil depth. The underlying idea is to pool and data-mine soil and environmental covariates accounting for spatial and temporal variations to build a rich data resource that enables the derivation of various soil realizations.

In the STEP-AWBH model, the spatially-explicit STEP factors capture the relatively stable soil forming factors within a human time frame, whereas the spatially-explicit AWBH factors describe the temporally dynamic environmental conditions through time. For example, the S factor could be populated by various maps or data that describe soil characteristics, including

- available soil taxonomic data (e.g., soil order, great groups)

- soil drainage class map
- soil texture map (clay, silt, sand content)
- soil organic matter map.

The STEP-AWBH model acknowledges that soil formation acts over shorter, intermediate, and longer periods of time dependent on the genetic processes involved to infer on a specific soil characteristic or condition of interest. For example, soil carbon accumulation may be influenced by short-term environmental conditions (e.g., severe thunderstorms and waterlogging) and superimposed long-term effects (e.g., increased mean precipitation rates over the past 30 years) that reduce decomposition rates. Both effects on soil formation are important and can be accommodated through assembly of AWBH datasets.

The AWBH factors allow capturing spatially and temporally varying environmental conditions. For example the W factor could the described through

- soil moisture derived in weekly or monthly intervals over a 2- or 3-year time period for all pixels within a region
- temporally aggregated sets (e.g., average, minimum, and peak soil moisture over a 5-year period) for all pixels within a region.

For instance the A factor could be populated using

- long-term mean precipitation (1970-current)
- aggregated precipitation during summer months
- maximum temperature last year
- maximum temperature over the past 30 years
- daily or weekly precipitation
- monthly long-term records of solar radiation.

Sequences of hydrologic, climatic, and biotic ecosystem properties can be assembled to populate AWBH factors using remote or proximal soil sensors. The H factor represents different anthropogenic forcings that can act across 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, pollution (e.g., an oil spill), disturbances, overgrazing, population growth, and others. The STEP-AWBH variables are harmonized into a common geographic map projection to support spatial extraction to pedon locations. The underlying idea of MSM is to assemble an exhaustive set of STEP-AWBH data for a geographic domain because it is not known a priori which of the variables and combinations of variables will have a significant effect on soil genesis and formation on the soil properties and phenomena. The STEP-AWBH data in the MSM theory represent the "potential soil reality", whereas the DSM methods reduce the attribute space and identify those STEP-AWBH variables that govern the soil property/phenomena of interest, and hence, allow assessing the "actual soil reality".

(2) Methods: DSM methodologies were described by McBratney et al. (2003) and Grunwald (2006) and range from fuzzy logic, geospatial, geostatistical, statistical to deterministic methods. Recently, mixed methods (e.g., Regression Kriging) and integration of methods have emerged in the DSM discipline. Such meta-methodologies allow customizing the selection and bundling of methods to create soil models in dependence of scale, needs, and specifications (e.g., explicit uncertainty assessment accounting for fixed effects and spatial random effects) embedded within a shared theory of harmonized and standardized soil-environmental data. Since a meta-methodological approach is pluralistic it allows ranking of methods to identify a "better than other" performing approach and eventually convergence of findings from a multiplicity of applied methods and perspectives. Importantly, consistent side-by-side comparisons are facilitated by the MSM because the same harmonized soil and environmental datasets are used to generate multiple digital soil maps and models. It is critical to note this advantage of MSM when compared with DSM applications documented in the literature because these were derived with soil and environmental data, protocols, methods, and verification approaches that differ widely.

Another advantage of meta-methodologies is that they foster synthesis which occurs when disparate data, concepts, paradigms or theories are integrated in ways that yield new knowledge, values, insights, understanding or explanations (Pickett et al., 2007; Carpenter et al., 2009; Peters, 2010). The following synthesis pathways applied to MSM can be distinguished.

Methods include direct field observations (1) and fuzzy based logic based methods (2) that both involve some subjectivity. The integration of lab, field, and proximal soil data (e.g. visible/near-infrared (VNIR) and mid-infrared spectroscopy) (3) and active and passive remote sensing derived data (4) have gained widespread adoption in DSM. The integration of soil and environmentally ancillary data pooled into relational databases (5) is an essential step before applying some of the integration methods. Literature reviews that subjectively compare and discuss DSM approaches and applications (6) provide some bias due to the selection by authors. The mapping of soil properties and classes based on taxonomic systems (7) acknowledges the boundaries of groupings ex-ante, whereas statistical clustering methods adopt a posterior approach to classify soils (8). Empirical field observations are critical in DSM to populate models and to verify them (9). Probably the most dominant approaches in contemporary DSM are soil predictions/estimations based on methods that fit inputs (e.g., STEP-AWBH variables) and outputs (e.g., a target soil property) (10). These integration methods include regression methods, such as multi-variate regression and modern regression methods (e.g. regression trees) as well as data mining methods, such as Support Vector Machines and neural networks. Meta-analysis is less prominently represented in DSM applications due to the difficulties to harmonize soil data that often were collected with different protocols, sampling designs, and/or analytical methods. Ensemble models have blossomed in the DSM community using internal ensembles (e.g., Random Forest) or external ensembles (e.g., intercomparisons among different DSM application types) (12). Recently, sequential analysis (13) combining various methods in staggered fashion have been adopted to fill data gaps, fuse data and methods (e.g., use VNIR to estimate soil organic carbon (SOC), derive bulk densities using a pedotransfer function, apply a regression method to estimate SOC stocks, spline SOC vertically and then use an interpolation method to estimate SOC stocks across a region). The inherent risk in (13) is substantial error propagation through the multiple steps of the analysis. Pedotransfer functions (14) have been widely used to infer from simple to measure onto more costly to measure soil properties. Aggregation (15) and scaling (16) methods apply DSM methods across escalating spatial and/or temporal scales and are still constraint by our limited understanding of scaling effects on soil properties and phenomena. Multi-agent based analysis (17) is rooted in autopoiesis which adopts the view that members of ecosystems (e.g., humans, organisms) self-create the system. The autopoetic perspective illuminates the inner choices made by agents of the ecosystem as they actively participate with and enact their environment. These methods (e.g., swarm models) are rarely applied in DSM, but have potential to enhance existing ones. Spatial integration of soil and environmental covariates (18) using Geographic Information Systems and geostatistical methods are widespread in DSM, whereas pedodynamic, process oriented models that simulate soil genesis are sparsely represented in the DSM literature. Soil change and evolution based on scenarios (20), backcasting using historic and contemporary soil datasets to assess soil change (21) (e.g., SOC sequestration) have gained much interest and attention recently. Soil projection models (22), similar to climate change projection models, are anticipated to be developed in the near future.

(3) <u>Identification of the purpose, intent and/or motivation</u>: Many of the methods (Figure 3, (1) to (22)) are applied in various combinations to create digital soil maps, mainly soil properties and classes (Grunwald, 2009). She adamantly outlined that there is no universal equation or digital soil prediction model that fits all regions and purposes. The gaps between "*the best* soil map and *the best* soil model" that describe soil evolution spatially-distributed at global scale and at a resolution that captures the underlying variability of multiple soil properties and aggregate metrics (such as sustainability) and our current data, tools, and DSM approaches are evident. The MSM has the potential to address these gaps and generate various soil realizations, maps, and models across various scales and resolutions.

3 FINAL REMARKS

3.1 *Is Meta Soil Modeling Madness or a Viable Option for Digital Soil Mapping*

The MSM provides a pluralistic theory for DSM in terms of data, methods, and paradigms. The benefits of a pluralistic approach to DSM are seen in its inclusiveness accommodating multiple needs and values we associate with the preservation and functioning of soil resources. The MSM also entails global digital soil property maps (such as those envisioned by GSM) as realizations out of a broad spectrum of possible soil realizations. The inherent risk of a pluralistic approach aiming to create this spectrum of possible soil realizations disclosed by multiple philosophical perspectives to reveal the 'multiple soil object' is a path of infinite DSM possibilities – or simply a path of madness. In essence, the theoretical demands of a full-spectrum MSM are not congruent with practical DSM capabilities and available resources.

This "soil mapping madness" of the MSM can be addressed by the guiding principle of enfoldment outlined in Integral Methodological Pluralism (IMP) that asserts that all methods and paradigms are somewhat true and adequate, but some are more encompassing, more inclusive, more holistic than others. Enfoldment refers to the integral process based on the premise that if one method/paradigm/pathway includes the essentials of another and then adds further synthesis, such that it enfolds or includes the other, then the latter can be legitimately be claimed to be more integral. In essence, the claim is that some methods/integration pathways are better – more inclusive, comprehensive, and insightful – than others (Wilber, 2007; Esbjörn-Hargens and Zimmerman, 2009). Hence, the main goal is to discern those integration pathways of the MSM theory that enfold or synthesize our knowledge and understanding about soils from other pathways that have less value. This process of enfoldment may involve to (i) simplify the complexity of a DSM approach (e.g., identify a parsimonious model that has similar predictive capabilities to model soils than an over-parameterized, complex soil model), (ii) complexify existing DSM models/approaches (e.g., STEP-AWBH is more complex and encompassing than

CLORPT), (iii) dialectic (i.e., use thesis and antithesis to derive synthesis), (iv) antagonistic (i.e., demonstrate that a DSM approach is of less value/poorer performance than another one through cross-comparisons in different regions within a given MSM domain), (v) integral (i.e., integrate more perspectives/worldviews into an approach to map/model soils), or (vi) synthesize (i.e., add value to an existing DSM approach; e.g., better predictive performance of a soil model or added capabilities to assess uncertainty in addition to estimations of soil properties). The broad spectrum MSM theory is juxtaposed to facilitate enfoldment to better understand the soil-ecosystem continuum because it (i) formalizes DSM based on different perspectives/worldviews disclosing the 'multiple soil object', (ii) makes integration pathways more transparent to prioritize/select those that are "better in some way" than others, and (iii) allows intra- and intercomparisons of different DSM integration pathways (because the same inclusive datasets are used).

3.2 *Application of the Meta Soil Model (Part II)*

Although the MSM outlined in this paper is generic it will be tested and applied to DSM in the United States. The part II paper presents an integrated data structure consisting of legacy and contemporary soil carbon and environmental data with the vision to apply meta-methodologies/perspectives creating a Meta Soil Carbon Model for the United States.

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