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FEATURE

Practical guidance for deciding whether to account for soil variability when managing for land health, agricultural production, and climate resilience

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This paper provides practical guidance for determining when it is—and is not—worth considering soil variability when making land management decisions and implementing land restoration initiatives. It presents a two-part framework that can be used by farmers, ranchers, land use planners, and other natural resource decision-makers to determine whether or not it is worth modifying management in different parts of a field, pasture, watershed, or region based on differences in soil properties and processes. The "prepare" part of the framework includes five steps: (A) defining the management or restoration area, (B) defining the objective or objectives, (C) identifying key soil and topographic properties and defining functionally significant variability based on the objectives and costs of modifying management across the area, (D) acquiring soil maps and other soil information, and (E) accessing relevant local and scientific knowledge. The second part of the framework, "decide," includes seven questions, which are designed to determine whether or not management should be modified based on variability of key soil properties, and, if so, whether it is worth collecting additional soil information. The decision framework is presented in a figure and illustrated by a practical irrigation scheduling example.

> "*The farmers' plows were made of wood and leather and were designed to fit the nature of each particular type of soil lest they break or the limited animal power fail. Machine technology drove a steel wedge between man and his home. The farmer who was on intimate terms with his land grew to know it more remotely, for a steel plow need not take account of regional dirt as it slices through sod.*" (Williams 1974)

Soil variability has been studied by a variety of scientific disciplines. Soil scientists, hydrologists, environmental chemists, geotechnical engineers, and ecologists have all sought to understand the extent to which soil properties vary, the scale at which they vary, and the factors that cause them to vary.

The importance of understanding soil variability is arguably more important today than it has ever been, as the world faces the quadruple threat of climate change, land degradation, declines in nonrenewable fertilizer stocks, and increasing competition for fresh water. Soil variability is key to understanding and managing these threats in some landscapes, watersheds, and regions, and irrelevant in others.

Hans Jenny's (1941) *Factors of Soil Formation* formalized our understanding that soils vary as a function of five conditioning factors that are responsible for soil genesis: parent material, topography, climate, biology, and time. This understanding, which built on the work of Dokuchaev (1886), informed, to varying degrees, the development of most of the soil maps published in the twentieth century. Some, like the Genetic Soil Classification system used to generate New Zealand's first national soil map, were almost entirely based on this approach. This allowed soils to be mapped "from a few observations, and with knowledge of climate, landform, vegetation, and geology" (Hewitt 1992).

A limitation of the genetic approach for describing soil variability is that it does not result in a uniform hierarchical system that can be applied globally. The US Soil Taxonomy was developed with a strong emphasis on hierarchy based on how soil moisture influences the presence, depth, and thickness of epipedons, and diagnostic horizon (Stolt et al. 2021). While it references soil forming factors (Bockheim et al. 2014), Soil Taxonomy prioritizes the ability to develop systematic keys based on properties often associated with management limitations over pedogenesis when compared with, for example, New Zealand's original system.

The more recent statistical approaches to digital or predictive soil mapping do not a priori prioritize soil forming factors, nor are they necessarily based on a classification system. They do, however, inherently prioritize those soil forming factors that can be globally resolved using remote sensing imagery and that are correlated with differences in soil properties. Soil properties are typically independently predicted for each pixel (Poggio et al. 2021; Hengl et al. 2021; Rossiter et al. 2021). These approaches result in soil maps that can help to determine whether soil variability is worth considering, but the conclusion ultimately depends on the requirements

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of each land use and management system within a specific landscape.

The importance of accounting for soil variability when managing land was recognized long before individuals began to self-identify as soil scientists and to publish soil surveys. In New Zealand, the Māori had different names for different types of soil. This effectively resulted in a classification system, which focused on suitability for root crop production (Hewitt 1992). In East Africa, the differences in fertility and trafficability of "red" and "black" soils are well recognized by anyone who has had any agricultural experience or traveled dirt roads following a rainstorm. Brammer (2016) emphasized in the introduction of his book on the soils and climate of Bangladesh that even today, "Farmers [without referencing soil maps] know about these local differences, because they determine what crops they can grow in their different fields…"

The impacts that variability in relatively static soil properties have on a diversity of soil functions have also been widely studied. Variability in functionally significant soil properties at landscape to regional scales has driven land use decisions for millennia. Management-induced changes in soil properties can in turn lead to large local variation in relatively dynamic soil properties such as soil organic matter and nutrient availability, for example, within smallholder farming systems in Africa (Tittonell et al. 2005). Also, the entire field of "precision farming" is predicated on the assumption that varying soil management, particularly fertilizer inputs, can increase profitability. The increased profits are often associated with a proportionally increased nutrient use efficiency, which typically has positive environmental benefits by minimizing losses through runoff, leaching into the ground water, or (in the case of nitrogen [N]) conversion to a greenhouse gas (N_2O).

And yet we also know that in many landscapes, soil variability is insufficiently important to be worth managing for. This can be due to the cost of mapping, the cost of spatially varying management, or the limited economic or environmental benefits of spatially variable management. For example, sometimes what appears to be functionally significant soil variability fails to explain spatial variability in rangeland vegetation dynamics (Williamson et al. 2016). Surprisingly, while there is a large amount of literature and a number of decision support tools to guide soil-specific management (e.g., figure 1), there is very little guidance available to help land use planners and managers determine when the costs of soil-specific management are justified by the benefits. Similarly, scientists would benefit from a better understanding of the types of soil variability that are inadequately addressed by current approaches to mapping. For example, those working on digital soil maps could focus on refining models for particular soil properties in specific landscapes, rather than working to improve average accuracy and precision for all properties throughout the globe. Finally, policymakers need a framework for deciding where and how to target limited resources available for the development of soil maps.

The objective of this paper is to provide practical guidance on the use of soil information in effort to improve land management in the face of climate change. Like many, if not most frameworks, the concepts presented are not new, yet the fact that they are rarely applied supports the need for a new presentation of them. Our framework should resonate with both those who would prefer to ignore soil variability, and those (including many soil scientists) who believe that soil variability nearly always matters. We hope that this framework will help support efficient and effective stewardship of agricultural landscapes for climate change adaptation, mitigation, and other outcomes.

FRAMEWORK DEVELOPMENT

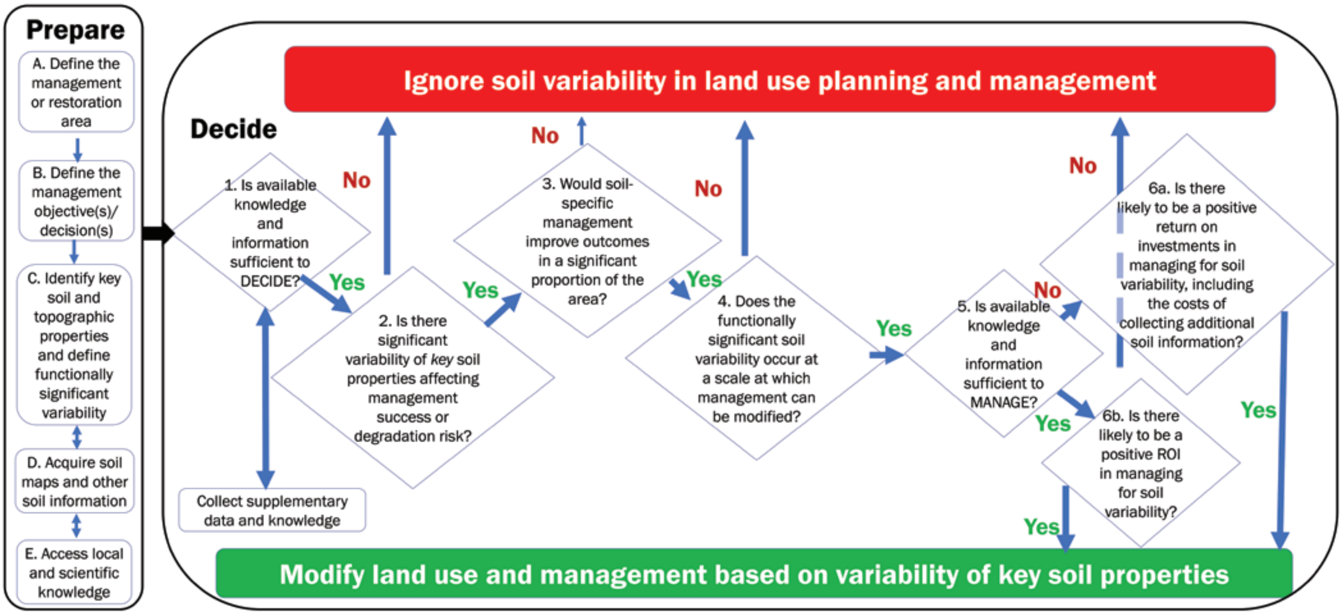
Development of the framework was informed by hundreds of conversations, e-mail exchanges, and workshops associated with the development of the global Land Potential Knowledge System (LandPKS) app (Herrick et al. 2016; https://landpotential.org). Early promotion of the app was justified by the assumption that

Figure 1

New Mexico State University's "Pecanigator" irrigation slide rule (Kallestad et al. 2008).

Figure 2

Framework that can be used by farmers, ranchers, land use planners, and other natural resource decision-makers to determine whether or not it is worth modifying land management based on differences in soil properties and processes.



Example: Does soil variability need to be considered for irrigation scheduling on a typical pecan farm in the Mesilla Valley of southern New Mexico, USA? See Box 1 for more information.

1. Yes. Soil maps indicate that there are soils with virtually every texture class.

2. Yes. Texture variability results in significant variability in available water holding capacity.

3. Yes. Irrigation frequency can vary by 2X or more depending on texture.

4. Yes for drip and sprinkler irrigation. Flood irrigation can be improved but not always fully optimized where soil boundaries occur within fields.

5. Not always due to the fact that these are flat, alluvial soils, which are difficult to map.

6a. Yes, if rapid field determinations of soil texture are made. Perhaps, if paid lab analyses are used.

6b. Yes, particularly as water becomes more limiting in the Rio Grande Basin.

the costs of site-specific soil characterization and identification were nearly always exceeded by the value of the information generated. This assumption was frequently challenged, and sometimes demonstrated to be false. In nearly every case the conversations ended with the questions, (1) "Is it worth managing for soil variability?" and if so, then (2) "Do I need to make any additional observations or measurements?"

In response to these concerns, we developed the framework to lead the user through a logical sequence of information gathering and interpretation, resulting in responses to both questions.

In preparation for framework development, we reviewed the current and historic literature on soil variability and soil mapping. We also referenced several of our own published and unpublished comparisons of different soil map products (Buenemann et al. 2023). Finally, we informally evaluated and refined the approach based on a variety of conversations with individuals who were attempting to answer one or both questions.

THE FRAMEWORK

The resulting framework is summarized in figure 2, with each step described below. The framework is divided into two main sections: Prepare and Decide. This structure is designed to allow the reader to quickly review the decision framework (Decide) and then iteratively reference the more detailed sections (Prepare) only where necessary.

Prepare–A: Define the Management or Restoration Area. In addition to defining the external boundaries, any land within management area where management will not be changed should be identified. Areas not subject to management change can be excluded from the remaining steps.

Prepare–B: Define the Management or Restoration Objective or Decision. Every one of the subsequent steps in both Prepare and Decide depends on clearly defining the management or restoration objective or objectives that are being pursued within the management area. Where possible, the specific decisions required to address the objective(s) should also be identified at this stage, while recognizing that some decisions may depend on responses to questions described in subsequent steps.

Prepare–C: Identify Key Soil and Topographic Properties and Define Functionally Significant Variability. Deciding which soil properties affect land use, management, or restoration success or degradation risk is the most important and often most challenging step. A common mistake is to start with a list of soil properties, such as soil texture and total N. Instead, we suggest beginning with a list

Box 1

Key soil and topographic properties for irrigation scheduling.

In the face of climate change and increasing competition for fresh water resources, soil water management is emerging as one of the greatest challenges. Irrigation scheduling is a management decision that depends on an understanding of how soil mediates the climate-driven supply and demand for water. The most important soil properties for determining irrigation frequency and amount include (1) plant-available water holding capacity, or the maximum amount of water that is accessible to plants that can be retained within the plant rooting zone; and (2) infiltration rate, or how quickly water moves into the soil (infiltration rate). Infiltration rate is especially important on sloping soils and for irrigation systems that rely on gravity to distribute the water across the field. In some soils, optimal soil water management also depends on drainage because of its effect on oxygen (O) availability in the rhizosphere. Soil water storage capacity, infiltration rate, and drainage are all strongly related to soil texture, while soil depth is more likely to be important where it is less than the typical crop rooting depth.

The same logic is used to determine the *functionally significant variability* in the property. For irrigation frequency, we define "functionally significant variability" as that that results in a difference in irrigation frequency that is large enough to be *practical* to implement, and would result in significant differences in production, production costs, or both.

New Mexico State University in the United States clearly used this process when they developed their simple "Pecanigator" slide rule irrigation scheduler, which uses spatial differences in soil water holding capacity based on soil texture, together with temporal differences in plant water requirements (figure 1) (Kallestad et al. 2008). They defined a minimum two-day difference in irrigation frequency during the peak irrigation period as the threshold based on models, empirical studies, and farmer feedback (see Prepare–D). Based on this, and the relationship between soil texture and water holding capacity soils in pecan (*Carya illinoinensis*)-growing regions of New Mexico (Prepare–C), they provided irrigation *frequency* recommendations throughout the growing season for just four texture classes. Using a minimum one-day difference in frequency would have complicated their system by increasing the number of texture classes for which unique recommendations were required. For irrigation *amount*, they collapsed these four texture classes into just three: fine, medium, and coarse. An advantage of this process-based approach is that it allows climate change scenarios to be seamlessly integrated.

of the key land use or management needs, such as irrigation scheduling or land degradation avoidance. Then identify those soil properties that affect management outcomes. Finally, define the functionally significant variability, or the amount of variability in a soil property, that would trigger a management response.

For example, for alfalfa (*Medicago sativa*) irrigation, the difference in soil water holding capacity associated with a 1 texture class difference (e.g., silt loam versus clay loam) may not be sufficient to justify managing these two soils differently, but it might for more sensitive and high-value wine grapes (Box 1). Similarly, the difference between a 1% and 5% slope on a sandy loam is unlikely to have a significant effect on soil erosion on most perennial grasslands, regardless of grazing management, while in an annual cropping system the 5% slope would require much more intensive soil conservation practices to limit degradation. Consideration of land degradation also applies to a number of other processes, including salinization (Box 2).

Prepare–D: Acquire Soil Maps and Other Soil Information. Traditional and digital soil maps provide the starting point for both predicting soil type (identified by series or taxonomic class) and soil properties (defined as a measurable property at a given depth for a specific location). Soil maps can also be used to predict how much soil properties are likely to vary within an area.

Most traditional soil maps provide five important types of information: (1) a list of soils that have been identified in each type of soil map unit, (2) the average proportion of the area covered by each soil in a typical map unit for each type, (3) the association of specific soils with particular landscape positions or landforms within the landscape, (4) the taxonomic classification, and (5) values for selected properties at different depths for a representative pedon. The properties may be measured, observed, or predicted based on known relationships with other properties (such as plant available water holding capacity based on texture, bulk density, and soil organic matter). Finally, some soil surveys also include *interpretations* that may include management limitations and requirements and suitability for particular land uses.

Where these interpretations do not exist, the taxonomic class can be used as a general guide. As discussed in the introduction, a key limitation of taxonomic soil classification systems is that it is impossible for a single classification system to be optimized for all land uses, regions, climates, or crops. For example, plant available water holding capacity is often the most important differentiating property for dryland cropping (Ippolito et al. 2021), but a system focused on soil water would lump soils with very different texture, mineralogy, and pH values. Most of the highest taxonomic levels of both The Food and Agriculture Organization of the United Nations (FAO)'s and US soil classification systems are associated with differences in properties that have significant implications for management. A management interpretation summary for each of the FAO's subgroups is accessible through the LandPKS app (https://landpotential.org/).

Digital soil maps generated with statistical models independently predict each property for each location. A comparison of soil property values among pixels within the management area can be used to provide some indication of soil variability, and more recent digital soil map products (e.g., SoilGrids v2.0, iSDAsoil v1.0f) provide predictions of model uncertainty at each pixel.

Traditional and digital soil maps have strengths and limitations that make each more useful when it is interpreted together with the other. Traditional soil maps can often provide a better estimate of the maximum range of variability for a particular property expected within a polygon because they provide lists of soils that have been described in the area, rather than just

Box 2

Key soil and topographic properties for degradation risk.

Approaches like that described in the irrigation example have been applied to agricultural development projects designed to increase crop production throughout the world. Many of these projects have ultimately failed because they didn't consider soil- and topography-related differences in degradation risk. For irrigation, the greatest risk is often salinization, and the risk of salinization can vary tremendously within a soil texture class for soils with different mineralogy (Rengasamy 2006). Even simple tools, like the LandPKS app, can be used to flag potential degradation risk by applying simple tools like the 8-class Land Capability Classification system (Quandt et al. 2020) and accessing basic information about soil mineralogical constraints based on soil taxonomic classification. In the future, we expect that these types of tools will be directly integrated with soil erosion and other models to facilitate rapid assessments of degradation risk for different soil types (McCord 2021).

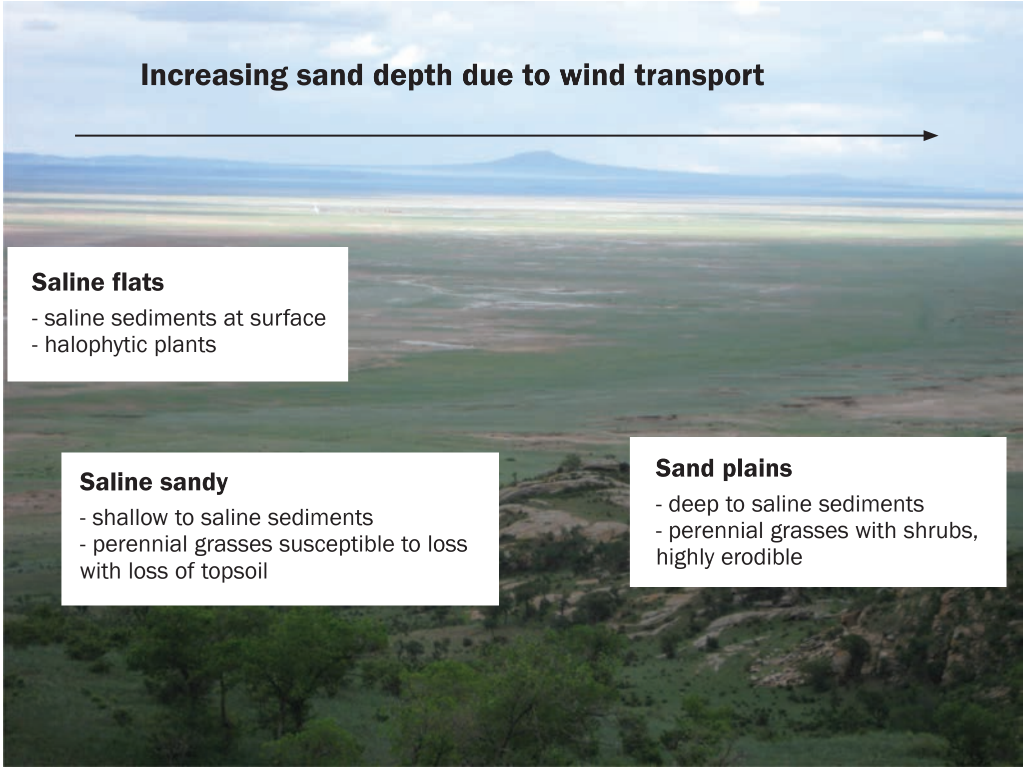
the most likely, though novice users of soil maps often assume that the first (dominant) soil listed is representative of the entire map unit. A quick comparison of the taxonomic classification of the soils listed for the map unit can be used to quickly determine whether there is likely to be significant variability in key properties.

Traditional soil maps are also more likely to identify abrupt boundaries because soil mappers typically prioritized visual indicators of spatial discontinuities in soil forming factors—particularly topography and parent material—in defining soil map units. A recent analysis confirmed that digital soil maps tend to smooth out variation in soil properties—a regression towards to mean effect. This results in an underestimation of high values, overestimation of low values, and a tendency to obscure or diminish the abruptness of discrete soil boundaries (Rossiter et al. 2022). Efforts are underway to improve the accuracy of digital soil maps, including through the integration of traditional soil maps as "priors" in the predictive models.

In contrast, digital soil maps are helpful because they suggest spatially explicit patterns of variability across the landscape, including within traditional soil map units. These patterns can be compared with the soil-landscape association information provided by traditional soil maps to predict where the different soils listed for a

Figure 3

Soil variability near Dalinour Lake in the Inner Mongolia Autonomous Region near Xilinhot, China. Varying depths of sandy sediments over saline lake sediments are associated with shifts in vegetation and vegetation change/soil processes.



particular soil map unit are likely to occur within the map unit.

Other helpful soil information may include topographic maps, including digital elevation models, as well as results of spatially explicit models that predict crop production, soil erosion, and nutrient runoff based on soil properties. Even a simple visual examination of aerial or satellite imagery showing vegetation patterns can be used to identify areas where variability in key soil properties may be sufficiently high to affect response to management (figure 3). For example, relatively subtle changes in soil depth over saline sediments, easily visualized, create important differences in rangeland plants and management considerations (Bestelmeyer et al. 2011). In some cases, this information can be used to refine or simplify soil variability based on soil maps. For example, a group in Ethiopia successfully predicted crop fertilizer response across a large region based on landscape position alone (Amede et al. 2020).

Soil-landscape modeling tools enable users to use terrain attributes, remote sensing data, and auxiliary information to predict the lateral and vertical distribution of soil characteristics. This approach is an attempt to quantify and automate the qualitative approach that has long been used by surveyors to map the distribution and characteristics of soils (Ziadat et al. 2015).

Prepare–E: Access Local and Scientific Knowledge and Information. Local knowledge and information, including that held by Indigenous peoples, farmers, ranchers, and pastoralists, can be invaluable in determining the extent to which soils vary in ways that affect production or the costs of production (Snapp 2022), even if this knowledge cannot always explain why or how production is affected. Scientific knowledge is useful for making predictions based on general relationships, such as knowledge that loamy soils hold more water, and acidic soils have lower phosphorous (P) availability than neutral soils. Yet scientific knowledge often misses complex interactions, such as those between differences in drainage and plant and livestock disease incidence. Scientists are also likely to miss subtle differences. For example, "differences in elevation of only a few centimeters can make significant differences in the crops or crop varieties that farmers grow" in floodplains of Bangladesh (Brammer 2016).

Statistical approaches to characterizing and evaluating the importance of soil variability can be usefully informed by both scientific and local knowledge at the initial stages. For example, local knowledge can be represented quantitatively by eliciting estimates and constructing probability distributions, which can be used as "priors" in Bayesian analyses. Scientific and local knowledge can also be applied to analysis results as a "logic check." Are the results consistent with both sources of knowledge? Can they be explained based on a scientific knowledge of soil processes? Do they reflect what a knowledgeable land manager would observe? If not, why not?

The following sections describe each of the six steps summarized in figure 2. In some cases, the steps can be followed in a linear sequence, while in others it may be helpful to iteratively revisit earlier steps.

Decide–Step 1: Is Available Information Sufficient to Decide? The first step of determining whether sufficient information is available to decide if soil variability needs to be considered in land use planning and management must be evaluated for each of Steps 2 through 6 below (figure 2). Based on the information generated in the Prepare section of this framework (e.g., management or restoration area, management scale and objectives, key soil properties, and variability thresholds), an initial assessment of data sufficiency can be made. Typically, less soil information is required to address these questions (Steps 2 through 6; figure 2), relative to the information required to incorporate soil variability in management decisions. However, in areas where soil variability is high and existing soil maps lack the needed accuracy (spatial and/or thematic) to characterize this variability, supplementary information will need to be collected (figure 2).

A key, and often unacknowledged, characteristic of available soil information is its accuracy. All sources of soil information, including spatial data, have some uncertainty (Lark et al. 2022). Uncertainty is often not reported, and when it is, can be difficult to interpret (ibid). In many cases additional soil information may be required simply to determine the accuracy of the existing information.

Where additional information about soil variability *is* needed, it can often be quickly collected through a brief field visit or phone consultation. For example, if a traditional soil map for the area indicates that the management unit includes two functionally different soils (Prepare–C above), but that one (dominant) covers an average of 80% of the map unit, and the digital soil map indicates a high level of uniformity for the key soil properties, a field visit would be limited to checking just several preselected locations where either or both soil surveys predicts that a different soil is *likely* to occur based on one or more of the following: (1) information in the traditional soil survey soil description (e.g., based on the map unit description of the distribution of soils by landscape position), (2) areas where the digital soil map predicts a different value for a key soil property at a specific depth, even if the predicted difference is not functionally significant, (3) local knowledge, or (4) visual observation of indicators suggesting differences in one or more soil forming factors, such as topography or climate as reflected in slope aspect. Observable characteristics of the location where a functionally different soil is identified can then be used to quickly identify and delineate other parts of the management unit covered by the contrasting soil.

This process of spatial extrapolation is the same used by traditional soil surveyors within a landscape or region in which the interaction of the soil forming factors results in similar, and therefore predictable, patterns (Dent and Young 1981). It is also the foundation for the statistical approaches used in digital soil mapping, which begin with a set of geo-located soil profiles for which soil properties have been measured, observed, or predicted, and use a suite of globally available properties, such as reflectance, slope, and aspect, to predict those properties throughout the globe using statistical models, while the accuracy of these models increases with the number of available field observations. For example, a statistical model using topographic and satellite data predicted soil depth in a 56 km^2 area in Ethiopia with an accuracy of 65% based on 25 field observations, or ~0.5 km^2. Accuracy increased to 98% when 180 field observations were used to calibrate the model (Mehammednur et al. 2013).

Decide–Step 2: Is There Significant Variability of Key Soil Properties Affecting Management Success or Degradation Risk? To address this question, compare the list of key soil properties and the minimum differences defined in Prepare–B above to soil variability based on the different sources of available soil information (Prepare–C). For the irrigation scheduling example described in Box 1, a farm with a silty clay loam and a clay loam could be irrigated with the same amount of water and on the same schedule because the water holding capacity of these two soils is similar. There is little or no value for this farm in continuing the analysis beyond Step 2 if the only management decision is irrigation management, given the decision space defined in Prepare–B. In contrast, a farm with sandy loam and clay loam soils, which have functionally different water holding capacities, would justify further consideration of the value of soil-specific management.

The first farm may need to consider, however, a different irrigation schedule if the *mineralogy* of the soils varies significantly with respect to salt (and particularly sodium [Na]) content. Soils with high salt contents and a sufficiently deep water table can be successfully irrigated with high quality irrigation water if there is sufficient water to periodically overirrigate, flushing the salts out of the root zone. This illustrates the importance of carefully reviewing the information from the Prepare steps, and particularly C ("Identify key soil and topographic properties and define functionally significant variability") when completing the Decide steps.

Decide–Step 3: Would Soil-Specific Management Improve Outcomes in a Significant Proportion of Area? Just because a soil property affects management outcomes does not mean that a soil-specific change in management can necessarily modify those outcomes. This may be either because it is not feasible to modify the property, like soil depth, or there are no management options currently available to address the limitation, such as a low pH soil that cannot be limed because lime is unavailable to the farmer. Decisions on the best pathway of management options to be implemented, which depend on land characteristics as well as other socio-economic factors, is an integral part of iterative land use planning (FAO 1993).

Decide–Step 4: Does the Functionally Significant Soil Variability Occur at a Scale at which Management can be Modified? This question is closely related to the previous one. For example, a study using repeat aerial photography coupled to soil mapping demonstrated that deep sandy soils in the northern Chihuahuan Desert are more susceptible to brush invasion than shallow sandy soils (Browning et al. 2012). However, in some parts of these landscapes, soil depth varies at a scale that is finer than the scale at which livestock grazing is managed, and in some areas too fine even for optimizing herbicide application. This also depends very much on the intended land use type. Some land uses require a stringent range of soil variability, while others can adapt and produce within a wider range of soil variability (FAO 1976).

Decide–Step 5: Is Available Information Sufficient to Vary Management on Different Soils? While soil-specific management may be justified by the available information on the degree to which soils vary, management requires a map reflecting how the key properties vary across the landscape. While highly accurate small-scale soil maps are desirable, even generalized maps of soil variability can result in significant improvement of management outcomes, as demonstrated by the use of soil management zones (Nawar et al. 2017).

Decide–Step 6a: Is There Likely to be a Positive Return on Investments in Managing for Soil Variability, Including the Costs of Collecting Additional Soil Information? If the response to Step 5 is "no," the costs of obtaining the necessary information must be added to the costs of soil-specific management. For relatively static soil properties, such as texture and depth, these costs are incurred just one time and may be depreciated. For relatively dynamic soil properties such as N availability, repeated mapping based on measurement or modeling may be required. Hand-held and tractor- or implement-based sensors combined with modeling and remote sensing imagery are rapidly reducing the costs of quantifying soil variability, with the return on investment (ROI) becoming increasingly positive even for the world's most resource-limited farmers (Snapp 2022). Equation 1 can be used to determine the overall ROI:

$$\sum_1^n [(\text{area covered} \times \text{ROI of soil specific management}) - \text{mapping cost}], \quad (1)$$

where n is the number of functionally different types of soil within the management area (from Prepare–B above).

Decide–Step 6b: Is There Likely to be a Positive Return on Investments in Managing for Soil Variability where Sufficient Soil Information is Already Available? If the response to Step 5 is "yes," the increased costs of managing for soil variability must be considered and compared with the projected benefits. Costs can include time and equipment. Benefits can include increased crop productivity and reduced input costs and degradation risk (Delgado and Berry 2008; Herrick et al. 2019). Soil-specific management often results in a shift in costs from inputs to labor, which can have broader social benefits, and there are a variety of other ecosystem services, including carbon (C) sequestration for climate change mitigation that can be supported through soil-specific management (International Resource Panel 2019).

A review of the costs and benefits can in some cases lead to consideration of changes in management. The irrigation example described in Prepare–B above assumes flood irrigation, which is difficult and costly to modify at subhectare scales. Drip and sprinkler irrigation systems, however, can often be optimized to the scale of individual trees. The equation provided in Step 6a can also be applied here.

THE VALUE OF SOIL INFORMATION

Throughout this paper we have assumed that there is hierarchy of soil information value through repeated references to "functionally significant soil variability." We recognize that determining the relative value of soil information is a nontrivial task and varies with management goals.

We also believe that simply applying this framework will help managers decide when soil information *does* have value, and which information is likely to have the most value.

A key to making the best possible decisions is to first understand and apply existing information, and then prioritize the collection of additional information with the highest value-to-cost ratio. The book *Consider a Spherical Cow* (Harte 1988) provides a motivational guide to using the best available knowledge and information. The book is not (despite the title) bovine-specific. "Value of information analysis" (Howard and Abbas 2015) can then be used to determine whether the benefits of additional soil information would outweigh the costs of obtaining it, and which soil information to acquire. Soil information is likely to have high value when there is large uncertainty in soil attributes that are likely to impact outcomes (Hubbard 2014; Luedeling and Shepherd 2016).

SUMMARY AND CONCLUSIONS

Key characteristics of the approach described here are that it is systematic, stepwise, and iterative. Most importantly, it emphasizes the consideration of multiple sources of knowledge and information, including traditional and digital soil maps, models, understanding of soil-landscape relationships based on the soil forming factors, local knowledge, and personal observations.

While the approach draws primarily from agronomic examples and focuses on farmer decision-making, it is intentionally generic and can be applied to land use planning. It can also be applied by civil engineers, or even a homeowner who is estimating the size of the leach field for a new or expanded septic system, which depends primarily on soil texture.

As described in Decide–6b, the approach can also be easily applied to C sequestration initiatives designed to support climate change mitigation. Fortunately, most of the key properties that control variability in C sequestration potential, such as soil texture, are also critical for crop production so the incremental costs of applying the framework to address multiple land use and management objectives are relatively low.

Scientists can apply the framework to focus research on those areas where there is greatest uncertainty in those properties where more information on those properties is likely to improve management outcomes, and where increasing our ability to quantify and map soil variability is most likely to be applied. For example, many of the Earth's most productive soils were formed on alluvial parent materials. In these landscapes, soil texture in the rooting zone can change over distances of less than a meter. A uniformly low slope gradient combined with a surface layer of uniform texture makes it extremely difficult to map these soils without digging a cost-prohibitive number of pits. New sensors, or systems that combine sensors, remote sensing, and modeling, are needed that can rapidly, reliably, and cheaply detect differences in subsurface texture across these large and important areas.

The response answer to the question, "Does soil variability matter?" will always be "It depends." We suggest that, in addition to increasing the information available to support soil-specific management, it would be helpful to convert the framework described here into a more quantitative and automated desktop decision support system in which the "Preparation" costs are minimized by prepopulating a geo-spatial platform with relevant available data and integrating some simple analysis tools. At the same time the decision support system should assist and encourage the user to carefully review the data and model results; as Brammer (2016) admonished in his description of his own extensive work in soil survey and land evaluation, "The data were analysed personally, not by computer, which meant that all the data were examined personally and suspicious data rejected." As the dryland ecologist Walter Whitford frequently stated, "There are statistical outliers, and there out and out liars."

For the question of whether or not "there is likely to be a positive return on investments collecting additional soil information," the answer is "there is no substitute for actually examining the soil and landscape" (Rossiter et al. 2022), but value relative to the cost depends on all of the factors discussed in this manuscript.

Finally, while the complexity of the framework is likely to overwhelm most managers in the form we have presented it here, the benefits of even a cursory application of it may have significant benefits, following the logic presented in *Consider a Spherical Cow* (Harte 1988).

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