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Soil classification as a tool for contributing to sustainability at the landscape scale and forecasting impacts of management practices in agriculture and forestry

Curtis Monger [a,b,*], Erika Michéli [c], Felipe Aburto [d], Danny Itkin [e]

[a] Dept. Plant & Environmental Sciences, Skeen Hall Room N127, Box 30003, MSC 3Q, USA
[b] New Mexico State University, Las Cruces, NM 88003, USA
[c] Department of Soil Science, Hungarian University of Agriculture and Life Sciences, Hungary
[d] Texas A&M University, College Station, TX, USA
[e] Soil Erosion Research Station, Ministry of Agriculture & Rural Development, Israel

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ABSTRACT

Industrial agriculture since the middle of the 20th century has provided bountiful food, but it has also altered and degraded soil physical, chemical, and biological properties on a continental scale. To combat this situation, sustainable agricultural practices are advocated, as well as retiring or "rewilding" some soils from agriculture and letting them revert to natural conditions for preserving biodiversity. Many scientific disciplines (biological, pedological, agricultural) are playing roles in sustainability. Soil classification can also play a role since its function is to group soil properties into soil types and create maps that show soil patterns across the landscape. In addition, classification is based largely on the genesis of diagnostic properties. Each diagnostic property has an evolutionary history resulting from factors → pedogenic processes → soil properties. Understanding a soil's genesis not only enables us to understand what soils are today, and which ecosystem and soil health functions they perform, it also enables us to know what they were in the past based on chronosequences and soil memory, and what they will likely become in the future. If, for example, a residual soil shallow to limestone bedrock (e.g., Leptosols, or Lithic Hapludalfs) is plowed, remains uncovered by vegetation, and is allowed to erode to bedrock, it is neither sustainable nor regenerative. If, on the other hand, a soil with a mollic horizon (e.g., Chernozem or Mollisol) that formed in deep loess with no restrictive layers is allowed to erode causing it to lose carbon, moisture storage capacity, and favorable structure, it can regain its sustainability and become regenerative through proper management, such as cover crops and conservation tillage. Similar examples can be found for soils worldwide that illustrate the role classification can contribute to soil sustainability and regenerative capacity at the landscape scale.

1. Introduction

Industrial agriculture involving large-scale, intensive production of crops has increased food production worldwide by technological advances in fertilizers, pesticides, herbicides, irrigation, farm machinery, plant breeding, and molecular biology. These advances when combined with monocultural practices have led to biodiversity loss, pollution, the emergence of new pests, erosion, and soil physical and chemical degradation. Thus, we are now faced with the challenge of maintaining high yields and securing food production, while at the same time conserving or improving soils that provide vital ecosystem services, such as purifying water, reducing flooding, decomposing organic matter, sequestering carbon, and providing habitat for medicinal plants and pollinators (e.g., Pretty, 2018; Al-Kaisi and Lal, 2020).

Sustainable and regenerative agriculture address the challenge of maintaining yields with the goal of not harming the environment. By definition, sustainable agriculture "conserves land, water, and plant and animal genetic resources, and is environmentally non-degrading, technically appropriate, economically viable and socially acceptable" (FAO, 2014a) and has many connections to broader sustainable development goals (UN-SDG, 2023). Regenerative agriculture aims to go beyond the "do no harm" principles of being "non-degrading" to being "enhancing"

* Corresponding author at: Dept. Plant & Environmental Sciences, Skeen Hall Room N127, Box 30003, MSC 3Q, USA
E-mail address: cmonger@nmsu.edu (C. Monger).

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(Burgess et al., 2019). It involves (1) minimizing or avoiding tillage, (2) eliminating bare soil, (3) encouraging plant diversity, (4) water percolation, (5) integrating on-farm livestock and cropping operations, and (6) minimizing pesticides and synthetic fertilizers (Lal, 2020; Newton et al., 2020; Giller et al., 2021; O'Donoghue et al., 2022).

Understanding soil's role in agriculture using soil classification can be traced back 3500–4000 years to ancient Greece and Chinese societies (Brevik and Hartemink, 2010), still farther to 10,500 years ago with the first domestication of plants (Zohary et al., 2012), and still farther yet to perhaps 100,000 years ago when humans began to exert ochre (a natural clay earth pigment) for art (Domingo and Chieli, 2021). Numerous papers have been written on understanding soil's role in agriculture using soil classification. The main purpose of the soil survey program in the US dating to the 1890s, for example, was to predict how specific soils would respond to management (Soil Survey Staff, 1951). In addition, recent treatises pertinent to the theme of linking soil classification and sustainable agriculture include papers by McBratney et al. (2014), Yusnita et al. (2020), Rossiter (2021), and Bouma et al. (2022). The purpose of this article is to illustrate not only how an understanding of soil classification can contribute to developing sustainable management practices in agriculture (i.e., conveying what a soil is and where it occurs across a landscape), but also as a forecasting tool for predicting what a soil is likely to become.

2. Soil classification: what a soil is now, what it was, and what it is likely to become

How can understanding soil classification be used as a tool for sustainable agriculture? By "tool," we mean "a device used to carry out a particular function" (NOAD, 2023). The particular function, in this case, is grouping data by soil type, mapping those soil types across the landscape, and predicting how a soil will respond to management decisions. The core idea consists of knowing what a soil is now (taxonomically), what it was in the past, and what it is likely to become in the future under different management decisions. What a soil is now is based on its current properties. What a soil was in the past can be inferred based on processes operating today (uniformitarianism) combined with chronosequences and soil memory (Targulian and Goryachkin, 2004). Combining the present and past provides a trajectory for making predictions about the future (Fig. 1).

Linking classification to management requires an answer to the question: How much change due to management must occur before the classification changes? A classification should not, for example, change after plowing the soil. Still, there must be a threshold beyond which management practices are significant enough to merit a new classification. To address this question the concepts of genoforms and phenoforms have been introduced (Droogers and Bouma, 1997). Similar to biology's genotype and phenotype, the genoform is the genetically defined soil series, while the phenoform is the result of different types of management. In their study in the Netherlands, three different phenoforms were formed as a result of different management in one soil series (the genoform). Further analysis of the concept recognized that phenoforms are not only variants of the genoform resulting from different management, their differences must be persistent enough that substantial management interventions are necessary to change them (Rossiter and Bouma, 2018).

2.1. "What a soil is now"

What a soil is now taxonomically is based on its quantitatively-defined diagnostic features. Examples of diagnostic features that control how a soil functions and have bearing on sustainable agriculture include the andic, argic, calcic, duric, fragic, gypsic, mollic, natric, petrocalcic, petrogypic, plinthic, spodic, umbric, and vertic. These diagnostic properties are used as classification building blocks in the World Resource Base system (IUSS Working Group WRB, 2022), Soil Taxonomy (Soil Survey Staff, 1999, 2022), and many other soil classification systems worldwide (Krasilnikov et al., 2009).

Diagnostic physical properties that have bearing on sustainable agriculture include bulk density, linear extensibility, coarse fragments,

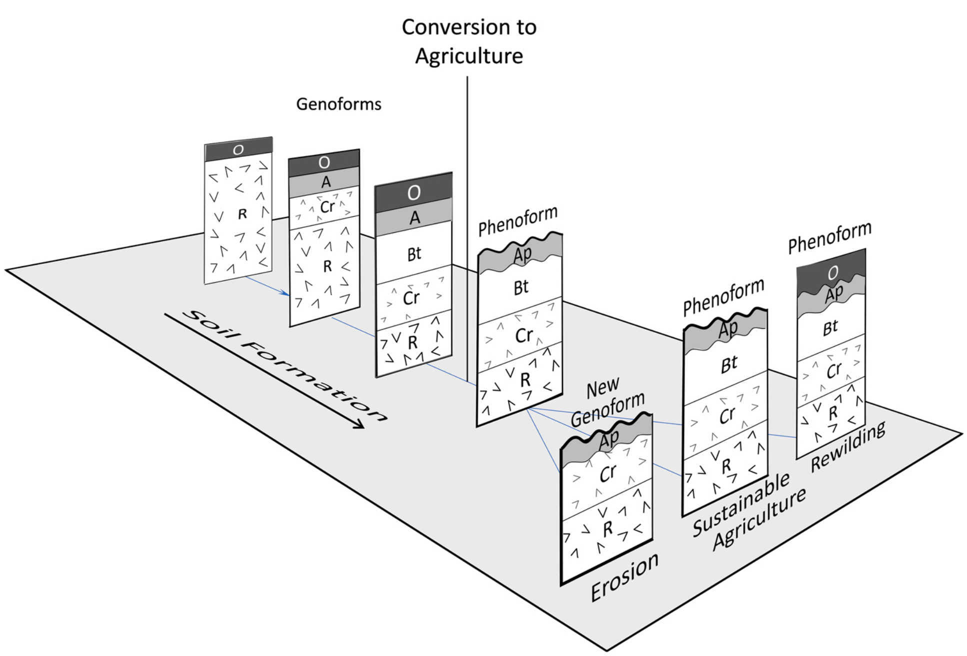

Fig. 1. Illustration of the development of a soil profile consisting of the formation of the Cr horizon produced by the weathering of bedrock (R), formation of a clay-enriched Bt horizon, accumulation of organic litter atop the profile (O), and the admixing of humus with mineral material (A). Conversion to agriculture results in the loss of the O horizon and transformation of the A horizon to the Ap plowed layer. With erosion, Bt material is incorporated into the Ap of a shallower profile to bedrock. With sustainable agriculture, the profile from former times is preserved. With rewilding, new organic litter is deposited on the relict Ap horizon. Only one new genoform (a genetically defined soil series) has been produced which resulted from management that allowed excessive erosion. Phenoforms are variants of the genoform resulting from different management, but are still the same series. Horizon symbols from Soil Science Division Staff (2017).

sand, silt, clay, and water retention. Chemical properties used in the definitions of diagnostics include cation exchange capacity, extractable acidity, base saturation, pH, nitrate concentration, calcium carbonate equivalent, gypsum content, anhydrite content, electrical conductivity, exchangeable sodium percentage, sodium absorption ratio, organic carbon, phosphate retention, and extractable aluminum, iron, and silicon. Additionally, mineralogy and field measurements of horizon color, thickness, and topography (e.g., tonguing) are used in the definitions of diagnostics.

The numerous ways diagnostic features can be combined—combinatorics—create classification systems capable of enormous versatility. Once classified, the suitability and limitations of a soil can be predicted for a multitude of land use interpretations (Table 1). Those especially applicable to sustainable agriculture include the fragile soil index, farmland classification, national commodity crop productivity index, non-irrigated and irrigated capability classes, ecological site names, potential for damage by fire, and predictions of crop yields in irrigated and non-irrigated management systems.

Despite the versatility of modern classification systems, more work is needed to quantify how soils pertain to sustainable agriculture. The effects of tillage, for example, which can change soil diagnostic features, should be expressed in soil classification (Yaalon and Yaron, 1966; Michéli et al., 2016). Toward this end, the WRB "terric" qualifier fits well for Anthrosols (i.e., soils "with long and intensive agricultural use"). The proposed Artesols Order (i.e., soils that form in "human-altered soils or in human-transported material" (Galbraith, 2020) could be enhanced to cover the classification needs for sustainable soils, such as terraced soils that have been sustainably used for centuries (Sandor, 2006; Boixadera et al., 2016; Itkin et al., 2022). Since many, if not most, soils have been impacted by humans, there is much opportunity in the classification systems to quantify the degree of alteration from their natural state (Calzolari and Filippi, 2016; Yassoglou et al., 2017; Çullu et al., 2018; ICGC, 2018; Monger et al., 2015; Poggio et al., 2021). Toward this goal, the genoform and phenoform combined with soil classification make much progress in articulating the impact of management on soils (Fig. 2).

2.2. *"What a soil was in the past"*

What a soil was in the past can be understood using two methods: chronosequences and soil memory. Chronosequences enables us to look backward and forward in time by holding constant the soil forming factors except time (Jenny, 1941; Buol et al., 1973). That is, we cannot travel in time, but we can travel in space and observe how progressively older soils have increasingly greater pedogenic development. "Soil memory" allows us to look back in time by analyzing "palimpsest-wise" and "book-wise" memory which is based on the sequence: factors → pedogenic processes → soil properties (Targulian and Goryachkin, 2004; Targulian and Bronnikova, 2019). Palimpsest-wise memory stores information about environmental factors in the solid phase of horizonated soil bodies. For example, a C-horizon parent material is transformed into a Bk horizon by the obliteration of sedimentary stratification and precipitation of pedogenic carbonate (Fig. 3). Book-wise memory stores information as layer-by-layer deposition of sediments. Once the factors and processes are established, inferences can be made about what that soil is likely to become under different management practices.

2.3. *"What a soil is likely to become"*

What a soil is likely to become is based on its evolutionary trajectory. This is the essence of using soil classification as a tool for predicting the consequences of management practices on sustainable agriculture and forestry. Having been converted to agriculture and experienced degradation, a soil's evolutional trajectory will take different paths depending on management decisions (Fig. 1). If erosion continues to alter and degrade soil, then harm to the environment as sediment source, loss of

Table 1
Soil classification is used to evaluate a soil's suitability, limitation, or potential for a variety of land uses. Suitability and limitation ratings, for example, are given below for multiple soil-use categories in the USDA-Soil Survey system WEB SOIL SURVEY, 2022.

SOIL USE CATEGORY	SOIL USE CATEGORY
Building Site Development	**NRCS Ecological Site ID**
Corrosion of Concrete	NRCS Ecological Site Name
Corrosion of Steel	Order of Soil Survey
Dwellings With Basements	Soil Moisture Class
Dwellings Without Basements	Soil Moisture Subclass
Lawns, Landscaping, and Golf Fairways	Soil Temperature Regime
Local Roads and Streets	**Land Management**
Shallow Excavations	Construction Limitations for Roads
Small Commercial Buildings	Drought Vulnerable Soils
Solar Arrays, Ballast Anchor Systems	Erosion Hazard (Off-Road, Off-Trail)
Solar Arrays, Soil-based Anchor Systems	Erosion Hazard (Road, Trail)
Unpaved Local Roads and Streets	Fencing, Post Depth 24 Inches
Construction Materials	Fencing, Post Depth 36 Inches
Gravel Source	Ground Penetrating Radar
Roadfill Source	Harvest Equipment Operability
Sand Source	Juniper Encroachment Potential
Source of Reclamation Material	Mechanical Site Preparation (Deep)
Topsoil Source	Mechanical Site Preparation
Disaster Recovery Planning	Potential for Damage by Fire
Catastrophic Mortality, Burial	Potential for Seedling Mortality
Catastrophic Mortality, Incinerate	Soil Rutting Hazard
Catastrophic Mortality Disposal, Pit	Soil Suitability for Industrial Hemp
Catastrophic Mortality Disposal, Trench	Suitability for Hand Planting
Clay Liner Material Source	Suitability for Log Landings
Composting Facility - Subsurface	Suitability for Mechanical Planting
Composting Facility - Surface	Suitability for Roads
Composting Medium and Final Cover	USFS - Road Construction
Emergency Disposal by Shallow Burial	Windthrow Hazard
Emergency Land Application of Milk	**Military Operations**
Rubble and Debris Disposal	Excavations for Vehicle Fighting
Land Classifications	Helicopter Landing Zones
Conservation Tree and Shrub Group	Vehicle Trafficability, Wet Season
Ecological Classification ID	**Recreational Development**
Ecological Classification Name	Camp Areas
Farmland Classification	Off-Road Motorcycle Trails
Hydric Rating by Map Unit	Paths and Trails
Irrigated Capability Class	Picnic Areas
Irrigated Capability Subclass	Playgrounds
Natl. Commodity Crop Productivity Index	**Sanitary Facilities**
NH Forest Soil Group	Daily Cover for Landfill
Nonirrigated Capability Class	Sanitary Landfill (Area)
Nonirrigated Capability Subclass	Sanitary Landfill (Trench)
Septic Tank Absorption Fields	**Waste Management**
Sewage Lagoons	Disposal of Wastewater by Irrigation
Soil-Based Residential Wastewater Disposal Ratings (VT)	Disposal of Wastewater by Rapid Infiltration
Soil Health	Land Application of Sewage Sludge
Agricultural Organic Soil Subsidence	Manure and Food-Processing Waste
Soil Response to Biochar	Overland Flow of Wastewater
Farm and Garden Composting	Slow Rate Treatment of Wastewater
Fragile Soil Index	**Water Management**
Limitations for Aerobic Soil Organisms	Embankments, Dikes, and Levees
Organic Matter Depletion	Excavated Ponds (Aquifer-Fed)
Soil Surface Sealing	Infiltration Systems, Deep
Soil Susceptibility to Compaction	Infiltration Systems, Shallow
Surface Salt Concentration	Irrigation, General
Vegetative Productivity	Irrigation, Micro (Above Ground)
Crop Productivity Index	Irrigation, Micro (Subsurface Drip)
Forest Productivity	Irrigation, Sprinkler (Close Drops)
Forest Productivity (Tree Site Index)	Irrigation, Sprinkler (General)
Iowa Corn Suitability Rating CSR2 (IA)	Irrigation, Surface (Graded)
Minnesota Crop Productivity Index	Irrigation, Surface (Level)
Range Production (Favorable Year)	Pond Reservoir Areas
Range Production (Normal Year)	Retention Systems, Lined
Range Production (Unfavorable Year)	Retention Systems, Unlined
Yields of Irrigated Crops (Component)	Subsurface Water, Outflow Quality
Yields of Irrigated Crops (Map Unit)	Subsurface Water System
Yields of Non-Irrigated Crops (Component)	Subsurface Water Performance
Yields of Non-Irrigated Crops (Map Unit)	Surface Water ManagementSystem

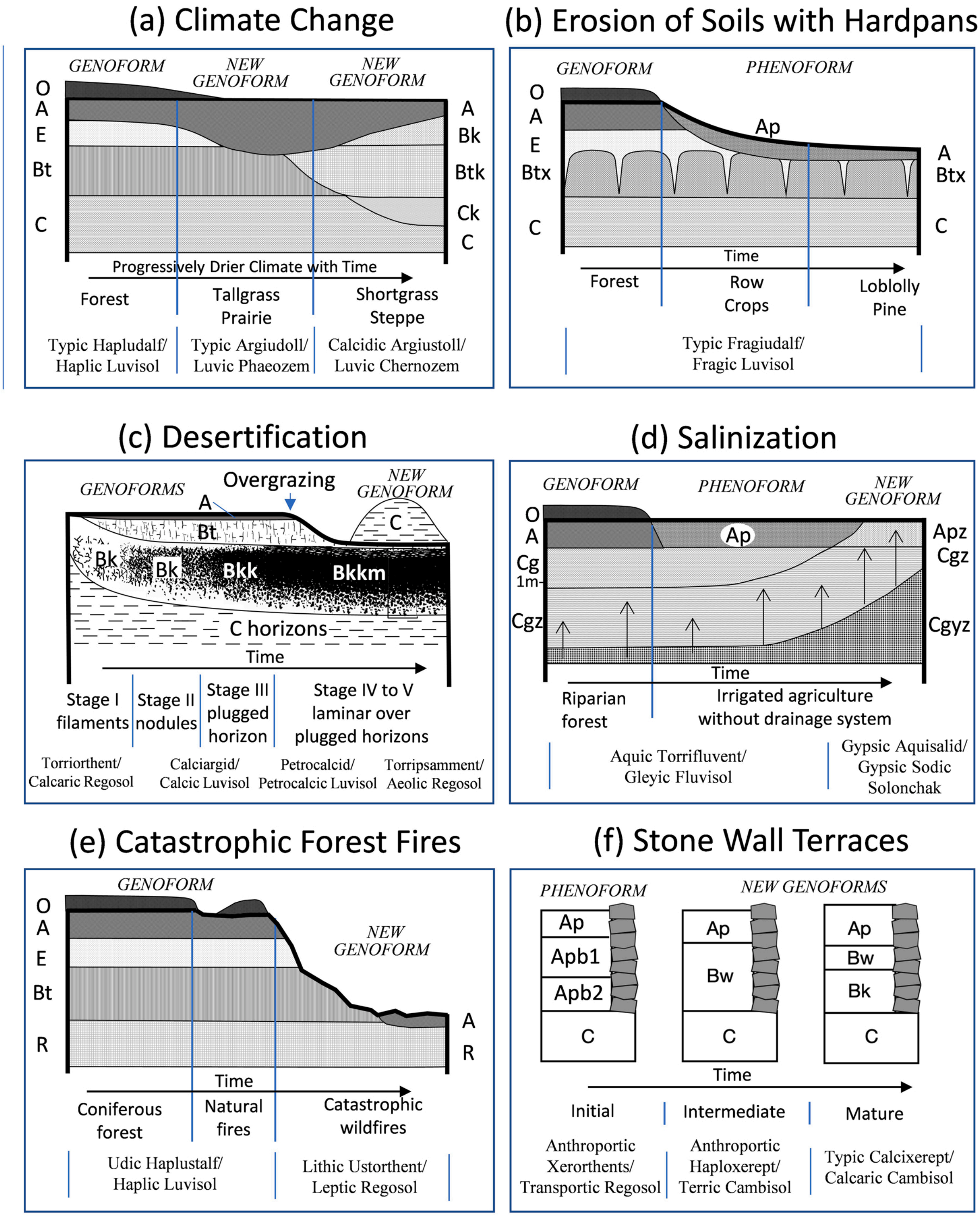

Fig. 2. Examples of soil change expressed as genoforms, phenoforms, and classification caused by management decisions and environmental change pertinent to soil sustainable agriculture. Classification is given in both Soil Taxonomy/World Resource Base systems.

carbon storage, and loss of filtering capacity will continue, and crop yields will decline as the soil functionality declines. This will put the farmer at a competitive disadvantage economically and reduce the additional benefits that soil provides to human communities. If, on the other hand, soil degradation is halted by sustainable agricultural practices, then harm to the environment will decline, crop yields will be maintained, and the farmer will not be subjected to a competitive disadvantage as the result of soil degradation. Still further, if a soil is allowed to return to its natural state ("rewilding") to regain functionality and provide habitat for biodiversity, then its profiles will return to a natural state in equilibrium with its environment.

Thus, based on classification, a soil's response to management and environmental changes can be predicted. Fig. 2(a), for example, shows the predicted response of a soil to climate change when the boundary separating the semiarid prairie from the humid forest migrates across a soil resulting in a change in the A-horizon (epipedon) and the formation of carbonates (Buol et al., 1973; Seager et al., 2018; Monger, 2014). In this case, new genoforms and soil taxa develop. Fig. 2(b) shows the response when a soil with a fragipan in a deciduous forest is converted to row crops leading to severe erosion that makes the soil unusable for

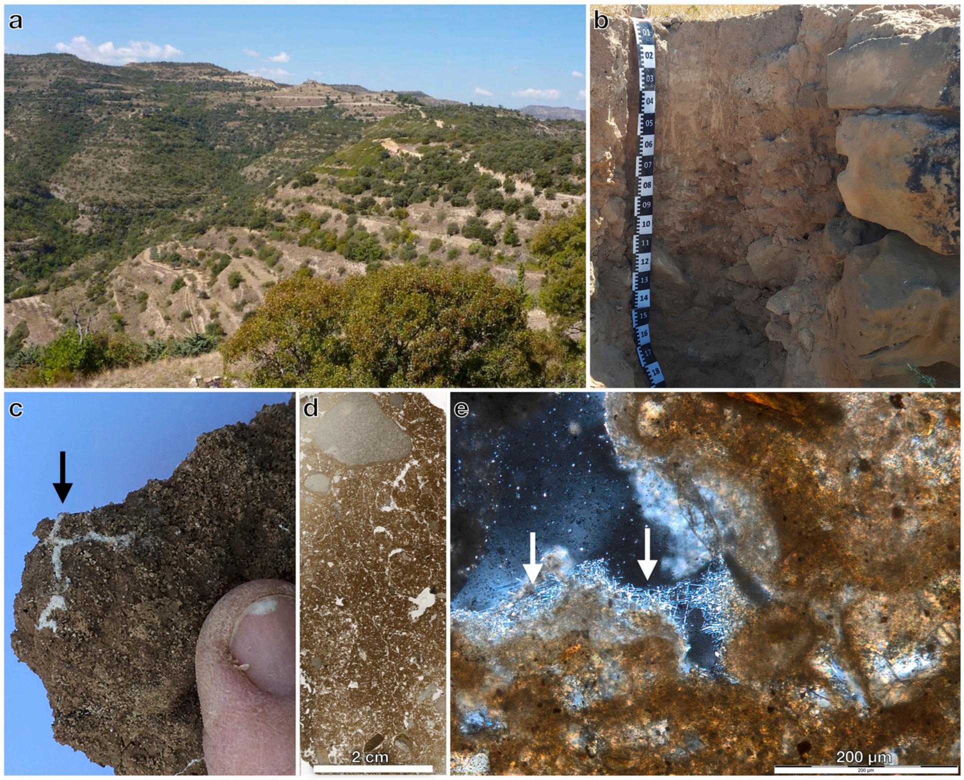

Fig. 3. Multi-scale images of terrace soils in northeastern Spain. In contrast to the typical genoform → phenoform sequence, this example starts with the phenoform and progresses to new genoforms. (a) Steep terracescape dating to the 1500 s and 1800s when the walls were constructed (Itkin et al., 2022). (b) Terrace soil profile showing the incipient development (coloring, structure) typical of many Mediterranean soils. (c) Biogenic development of calcium carbonate at the hand specimen scale, (d) Appearance of biogenic carbonate at thin section scale, and (e) Biogenic carbonate in crossed-polarized light showing its needle-fiber morphology interpreted to be fungal in origin.

agriculture (Ditzler et al., 1994; Graveel et al., 2002). A phenoform develops, but the classification remains the same. Fig. 2(c) shows the long-term accumulation of pedogenic carbonate in a soil beneath a desert grassland that was overgrazed in the late-1800s leading to severe wind erosion and coppice dune formation (Gile et al., 1966; Gile, 1966). Fig. 2(d) shows the effect of converting a riparian forest to irrigated agriculture without installing a drainage system to remove accumulating salts (Burrow, 2002). Fig. 2(e) shows the response of soils to natural forest fires versus catastrophic wildfires resulting from improper forestry management (Certini, 2005). Fig. 2(f) shows a soil developing behind a stone-wall bench terrace (Itkin et al., 2002). Rather than beginning with a genoform, this soil begins with a phenoform through anthropogenic deposition, thickening (soil aggradation) and neopedogenesis of human-altered and transported soil. Natural post-depositional pedogenesis form a Bw horizon and later a Bk horizon resulting in new genoforms. When stone-wall bench terraces are built on preexisting soil, both terrace and natural soils form one soil system. This soil, rather than degrading, can be sustainable for centuries and even millennia.

3. Soil classification as a tool for sustainable forest management, restoration, and ecosystem service provision

Soil classification has long been recognized as a relevant tool to differentiate and define forest site productivity, guidance for forest management, or quantify the impact on forest management activities (Fisher, 1928; Veatch, 1924). Soil Taxonomy, for example, is designed to organize, consolidate, and systematically group major trends in dominant quantifiable soil properties into discernable categories relevant to land management. Thus, soil classification systems provide maximum information on soil properties in a simplified form that can be used to differentiate and delineate soils in the landscape and plan management operations for different objectives (Fig. 4). The relevance of soil information and soil classification to define forest sites or examine relationships between soils, forest types, site productivity, and management effects is recognized among forest managers (Craigg et al., 2015). In fact, since the first publication in 1945, there has been an exponential increase in the amount of forest soil research focused on soil surveys (Knoepp et al., 2019).

Forest land intensification and the growth of exotic monoculture tree plantations have increased pressure on fragile soil resources and heightened the need to integrate soil information into forest site classification systems and management decision trees (Louw, 2016). It is well known that disturbances from intensified forest operations can significantly affect soil carbon and nutrient pools with relevant consequences to forest productivity and soil functions (James et al., 2021; Jurgensen et al., 1997). Crovo et al. (2021), for example, evaluated contrasting soil types (taxonomic orders) to test the differential response of deep soil nutrient stoichiometry to natural temperate forest conversion into exotic pine forest plantations. They reported that the change magnitude of C, N, P pools and their stoichiometric relations to this land use was significantly determined by soil type. Similarly, Premer et al. (2019) found that the response of different soil nutrients to intensive whole tree harvest depended on soil type (i.e., soil series) and that the effect on exchangeable soil cations was especially susceptible in some soil types.

Despite the relevance of classification to predict the response of soils to management this is rarely reported in many countries. For example, only a few forest restoration practitioners and researchers have adequately reported soil type or classification when evaluating soil recovery (Gatica-Saavedra et al., 2022). The latter limits the ability of restoration scientists and practitioners to truly evaluate and monitor forest ecosystem recovery. In addition, the lack of soil information

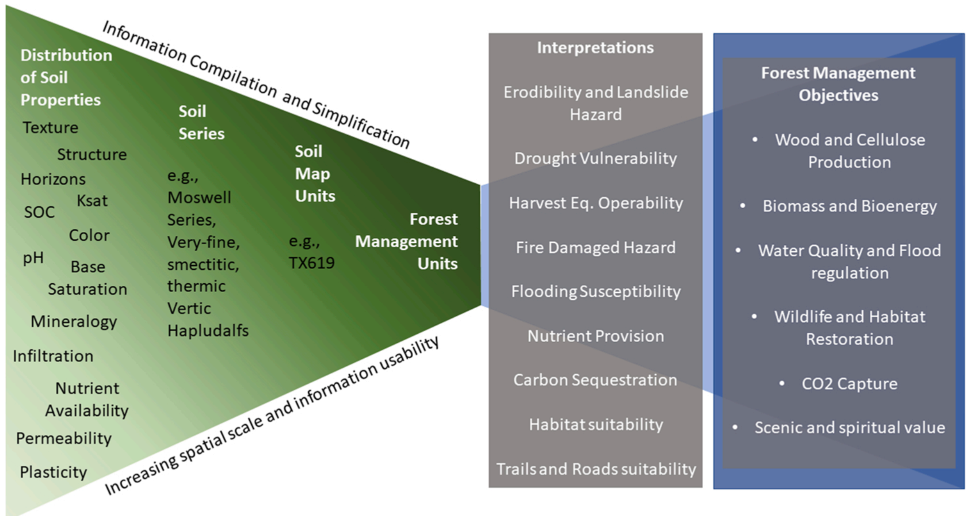

Fig. 4. Synthesis of soil properties information in soil classification and use for relevant soil use interpretation related to multiple forest management objectives.

impedes cross-comparison or result extrapolations.

Soil taxonomic classifications have been emphasized as an essential variable to predict soil carbon storage distribution, sequestration potential, and other ecosystem services provision at the landscape scale. For example, soil taxa information can be used to discriminate the spatial distribution of SOC and provide a basis for sampling design stratification (Wills et al., 2013). Shaw et al. (2015) found that incorporating soil taxonomic classification into the SOC density prediction model for forest soils in Canada could significantly enhance the model's ability to explain SOC distribution. They used redundancy analysis to report that the soil subgroup explained the largest proportion of the variance (18 %), more than any other considered variable (e.g., dominant forest species-genus and species). Similarly, Dalsgaard et al. (2016) found that modeled soil carbon density predictions can be significantly improved by including WRB soil taxonomic groups and drainage classes in Norwegian forests. This was attributed to the ability of these two parameters to capture dominant soil development and processes like podzolization and subsurface saturation that tend to increase carbon density in these soil systems.

Soil classification is also relevant for decision-making and accounting for nature's contribution or ecosystem services (ES) provision. Mikhailova et al. (2021) examined different approaches to quantify pedodiversity and ES quantification using soil taxa. They estimated that Mollisols had the highest organic and inorganic carbon storage midpoint value in the USA, equivalent to US$7.78 T, considering both the social cost of carbon (US$ 42 Mg emitted CO_2^{-1}) and CO_2 emission avoidance by storage. These ES estimations help synthesize and translate soil survey information into metrics that can be more easily used by decision-makers, planners, and forest managers to assess better the effect of land use and intensification in ES.

4. Conclusions

Most of the world's arable soils have been altered by human activities (Lal, 2007). Some soils are so severely degraded that agriculture is no longer possible (Fig. 5). Other soils, though degraded, have a high regenerative capacity, such as the soils formed in deep loess. In both cases, soil classification can contribute to sustainable agriculture as a tool for developing a denotative and connotative language that synthesizes soil properties and displays those properties on maps. This, in turn, enables us to describe a soil's suitability and limitations for many uses at the landscape scale. In addition, soil chronosequences and soil memory not only tell us about what a soil is now, they help us understand what it was in the past, and what it is likely to become in the future

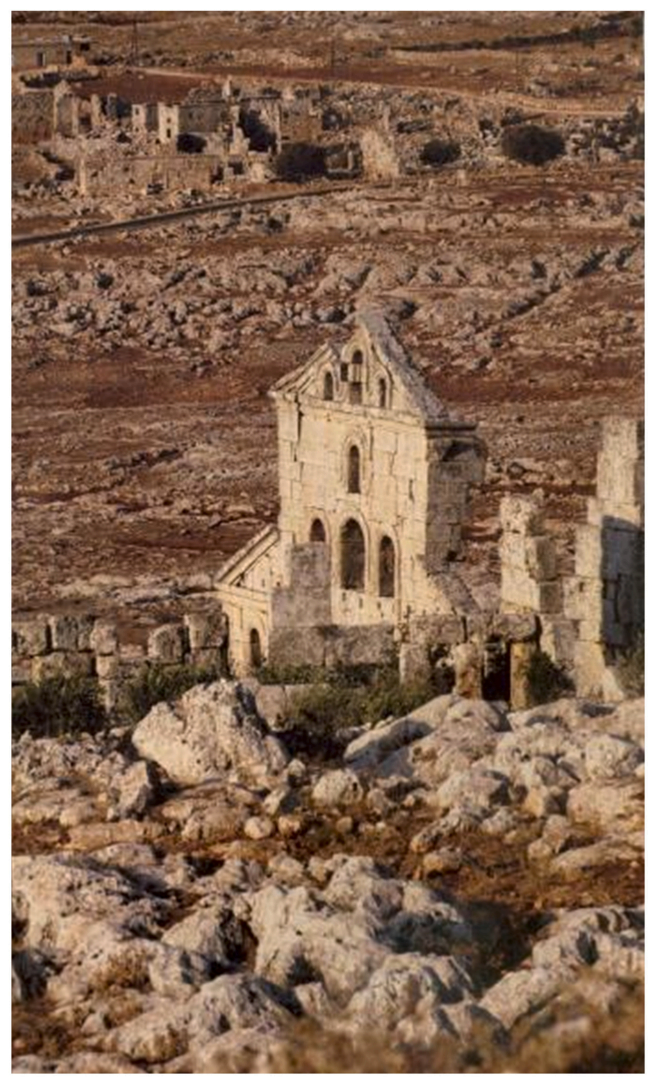

Fig. 5. Syrian landscape with shallow soils and exhumed bedrock no longer suitable for agriculture as the result of severe erosion that occurred centuries ago. Photo by Jim Richardson from Mann (2008).

under various management practices.

Despite their relevance, soil classification and genesis are underutilized for sustainable and regenerative agriculture at local and global scales. At local scales, they can be used to help farmers select and manage their best soils for growing crops under a changing climate, prevent degradation, restore soil health, and maintain habitat for biodiversity. At global scales and in a warming climate, soil classification and genesis can be used to predict where the most suitable soils for agriculture will be located and distinguish those from soils that should be devoted to habitat for biodiversity and ecosystems services.

For sustainable forest management and restoration, soil information is critical for properly defining goals and achieving objectives and monitoring metrics. Likewise, soil classification is an exceptional tool that condenses and groups numerous complex soil properties into unique hierarchical categories relevant to forest management. In addition, soil classification provides a basis for categorizing, identifying, and delineating distinct soil bodies in the landscape. A more ecosystemic perspective of forest management and restoration should always consider the information compiled by soil classification to derive interpretations and determine soil-based forest management units. This approach could allow managers and planners to more appropriately evaluate the impacts of forest operations, forest degradation, and land-use intensification on soils.

CRediT authorship contribution statement

Felipe Aburto: Writing – review & editing, Writing – original draft, Conceptualization. **Danny Itkin:** Writing – review & editing, Writing – original draft, Conceptualization. **Curtis Monger:** Writing – review & editing, Writing – original draft, Conceptualization. **Erika Michéli:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of Competing Interest

No conflict of interest are the result of the author and co-authors activities represented by this article.

Data availability

No data was used for the research described in the article.

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