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REVIEW

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Connecting forest soil properties with ecosystem services: Toward a better use of digital soil maps—A review

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Abstract

The soil supports many ecosystem services (ES) essential to human well-being. Rapid developments in digital soil mapping (DSM) allow the mapping of soil types and soil properties with improved resolution and accuracy. However, the potential of DSM to improve the assessment and mapping of ES is not fully exploited. To better understand this potential, we synthesized the peer-reviewed literature. We examined what empirical studies reveal about the role of soil properties in the assessment of four major ES provided by the forest: (I) timber production, (II) soil carbon storage, (III) regulation of water flow and provision of clean water, and (IV) the soil as a habitat for organisms. Results revealed that soil properties are strongly related to the provision of ES. Therefore, using DSM could greatly improve the assessment of the ES provided by forests. Several variables were related to specific ES regardless of region or ecosystem types, but others were found to be situation-specific (climate and soil type) and need to be considered at the proper scale or within a proper land classification framework. DSM products have the potential to greatly improve the assessment of ES by turning qualitative relationships between soil and ES to quantitative ones. This could also lead to the discovery of new soil–ES relationships. For this potential to be realized, progress should be made in mapping the most crucial soil parameters with greater precision and in promoting the use of soil parameters in ES assessment.

1 | INTRODUCTION

Human well-being depends on the quality of ecosystem services (ES) that are provided by the natural environment and the soil supports many ecosystem processes that are crucial to the delivery of these ES (Baveye et al., 2016). These services, referred to as soil services, include the storage of organic carbon, the regulation of water flow and water quality and the provision of habitat, physical support, and water and nutrients to plants and other organisms. The provision of these services is made possible by the capacity of soils to play the role of filter, buffer and transformation system for liquid, and solid and gaseous inorganic and organic compounds that pass through

Abbreviations: DOC, dissolved organic carbon; DSM, digital soil mapping; ES, ecosystem services; OM, organic matter; SOC, soil organic carbon; SOM, soil organic matter.

them (Figure 1). While the role of soil in supporting ES is well recognized, the use of digital soil maps is not developed to its full potential to improve the appreciation and mapping of ES (Bulmer et al., 2019).

Soil ES are supported by processes which are driven both by chemical, physical, and biological properties of the soil and by external factors such as climate, topography, organisms, and disturbances (Figure 2). Several soil properties are commonly assessed in soil surveys and their geographic distribution can be mapped. Other soil properties can be inferred from these primary ones with the use of pedotransfer functions. For example, a great deal of work has been dedicated to deriving pedotransfer functions that describe water flow and availability in soils (Toth et al., 2015). Soil processes define soil functions which are intermediate between ecosystem processes and ES and can be defined as the capacity of ecosystems to provide goods and services that satisfy human needs, directly and indirectly (de Groot et al., 2012). Finally, ES are the contributions of ecosystem structure and function—in combination with other inputs—to human well-being (Burkhard et al., 2012a). Figure 2 illustrates how the knowledge of specific soil properties is linked to appreciating and mapping ES.

Many studies have contributed to an improved understanding of how soil properties, together with other ecological factors, drive soil processes. The use of the full framework described in Figure 2, going from soil properties through to defining and mapping ES, is, however, very limited, especially in landscapes dominated by forests. Some examples of application in multiple-use landscapes can be found (e.g., Calzolari et al., 2016). The appreciation of the services provided by soil is important because their loss could be costly. At the European Union (EU) level, for example, their value is estimated to at least 50 billion euro per year (EC, 2021).

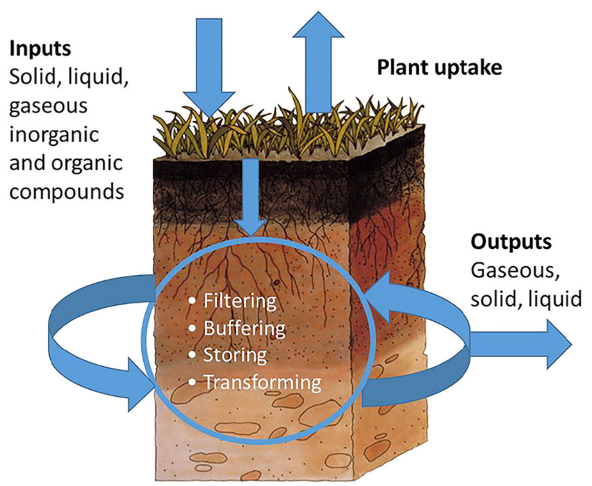

FIGURE 1 Soil as a regulator of the fluxes of gaseous, solid, and liquid inorganic and organic compounds, inspired from Blum (2005); soil profile from USDA-NRCS.

Core Ideas

- Soil properties are major determinants of forest ecosystem services (ES).
- Advances in digital soil mapping are generating better spatial estimates of soil properties.
- Soil properties are rarely used to evaluate ES.
- A literature review identifies how soil property maps could help improve the assessment of four ES.
- The ES considered are timber production, soil carbon storage, water quality/quantity, and habitat.

The EU Soil Strategy for 2030 provides a framework and concrete steps toward protecting and restoring soils and ensuring that they continue to provide ES such as food, timber, nutrient cycling, carbon storage, pest control, or water regulation (EC, 2021). Conceptually, using the term soil health recognizes that soil biology is a critical component for soil to have the continued capacity to function as a vital living ecosystem for plants, animals, and humans (Lehmann et al., 2020). Soil health provides the quality, along with quantity and accessibility, for soil security. This latter term is defined by McBratney et al. (2014) as the concept that concerns the maintenance and improvement of the global soil resource to deliver ES. The same terminology is widely used in reference to food and water security. There is recognition that without soil health and soil security, there is degradation and associated loss of ES that would result in preventing the achievement of the United Nation's Sustainable Development Goals (SDGs) (Lal et al., 2021).

Mapping ES, their potentials, or their vulnerability is therefore of high relevance to sustainable land use and management. Forest ecosystem classification (FEC) maps, which define homogeneous land units, have been traditionally used to evaluate ES and to guide forest management (Barnes et al., 1982). Approaches to define FEC do, however, vary across regions and countries. Most commonly, drainage, landform, parent material origin, and vegetation attributes are used to classify the landscape into homogenous units (Grondin et al., 2023; Mansuy et al., 2010). Traditional soil maps follow the same design; the land is classified into homogeneous units, which implies two important drawbacks: (1) that soil properties are not independent and (2) most often, the variability of soil properties within a mapped unit is not well represented (Bulmer et al., 2019).

The use of digital soil maps could potentially improve the assessment of ES if specific soil properties can be mapped at a relevant scale. The resolution and the accuracy of the information that is currently available about soil conditions and properties vary greatly across regions and are notably poor

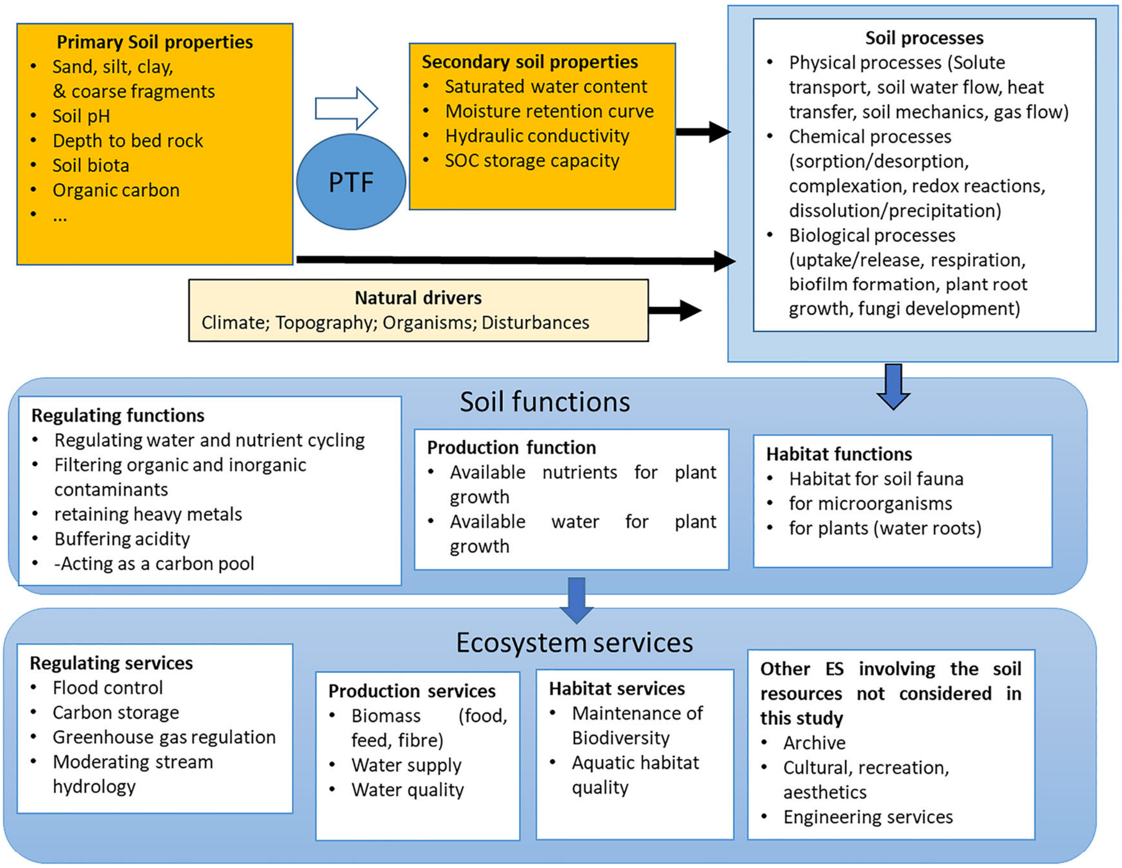

FIGURE 2 Framework of how soil contributes to ecosystem services (ES) (inspired from Greiner et al. [2017] and Baveye et al. [2016]). A glossary of the terminology used is presented in Supporting Information 1.

for uncultivated land (Baltensweiler et al., 2021; Hartemink et al., 2013). Soil maps for forested, grasslands, and other wildland types are typically coarse. Maps of standard soil properties like pH, texture, organic carbon content, or soil depth are generally not available at a resolution below 1 km, and these maps are often prone to large levels of uncertainty (Chen et al., 2022). The limited availability and quality (accuracy, level of uncertainty, and resolution) of soil maps represent a constraint both to science and to ecosystem management. Given the importance of soil properties as drivers of ecosystem processes and the challenges to land management brought by changing conditions, improved, accurate georeferenced soil information is greatly needed.

During the past two decades, global and national initiatives have supported the exponential development of digital soil mapping (DSM) techniques that make possible the mapping of soil types and soil properties with ever-increasing resolution and accuracy (Arrouays et al., 2017; Minasny & McBratney, 2016; Box 1). DSM has rapidly evolved from the research phase to practical use given the concomitant factors of increased availability of spatial data, availability of computing power for processing data, development of data mining, geographic information system tools, and geostatistics (Minasny & McBratney, 2016; Box 1). Relative to conventional soil mapping DSM methods are very explicit. DSM requires the use of geostatistical methods to fit and validate statistical models on georeferenced soil attributes (dependent variables) using environmental covariates that represent soil-forming factors (climate, vegetation, elevation, topography, lithology, hydrology, etc.) obtained from various sources, including remote sensing products and digital elevation models. Predictive variables and their respective contributions are identified, uncertainties assessments are produced, and results are repeatable. In North America, predicting modeling techniques continue to evolve, providing refined individual soil property map products for forested lands (Beguin et al., 2017; Heung et al., 2014; Kimsey et al., 2020; Mansuy et al., 2014; Mansuy et al., 2018). Surprisingly, despite the increasing production of digital soil maps and the information they provide, their utilization to assess and evaluate ES remains limited (Greiner et al., 2017). Several reviews have underlined that soil information is not being integrated to its full potential both in science and in ecosystem management (Chen et al., 2022; Greiner et al., 2017; Grundwald et al., 2011). The emphasis of ES assessment being largely on biodiversity conservation indices (Baveye et al., 2016). Possible reasons for the limited consideration of DSM-derived products in forest ES assessment include the complex, computer-based statistics

Box 1: Recent advances in digital soil mapping

Digital soil mapping (DSM), also known as predictive soil mapping or pedometric mapping in soil science, is the computer-assisted production of digital maps of soil types and properties. The international Working Group on Digital Soil Mapping (WG-DSM) defines digital soil mapping as "the creation and the population of a geographically referenced soil databases generated at a given resolution by using field and laboratory observation methods coupled with environmental data through quantitative relationships" (Lagacherie & McBratney, 2006). DSM allows for mapping soil properties at a finer resolution than traditional soil sampling techniques and the ability to represent spatially explicit gradual changes, something that was not possible with traditional maps that classified the landscape into discrete units (Bulmer et al., 2019; Heuvelink & Webster, 2001). This approach is advantageous when the soil classes mapped are not uniform or when the transition from one soil type to another is gradual, with few abrupt boundaries. In addition, it allows for an appreciation of the level of uncertainty and provides a more realistic representation of the independence between soil properties. Y. Zhang et al. (2018) emphasized that the quantification of ecosystem services on large scales lacks reliable data, a unified estimation method, and indication of result accuracy. The development of DSM products could be useful to answer these concerns. Currently, DSM products are becoming more and more available at different scales, from local to global. *GlobalSoilMap* is a global consortium whose aim is to produce global maps of twelve mandatory soil properties using state-of-the-art DSM techniques (Chen et al., 2022). These include depth to rock, plant exploitable depth, organic carbon, pH, clay, silt, sand, coarse fragments, effective cation exchange capacity, bulk density (whole soil and fine earth), and available water capacity.

to generate these maps, their varying accuracy and resolution, and the fact that the DSM is still a relatively young discipline and therefore poorly understood among soil scientists, land managers and policy makers (Arrouays et al., 2020).

The main objective of this review is to illustrate how information on the geographical location of specific soil properties, which could be produced with DSM, could help to better appreciate and map the ES provided by forest landscapes. We conducted a literature review to improve our understanding of the linkages between soil properties and four important ES provided by forest soils and to be informed on what soil properties should be mapped with greater accuracy to improve the assessment of ES provided by forest lands. Given the breadth of literature on these topics, our objective was not to review the entire literature, but to gather sufficient information to make the case that DSM could be useful in improving the assessment of ES compared to the traditional polygonal maps.

To achieve this objective, we reviewed the peer-reviewed literature that has investigated the relationships between soil properties and ES using empirical approaches to determine the factors that represented potential drivers of ES. We did not limit our search to a specific region. However, the results are strongly dominated by studies from temperate and boreal forests. When possible, we compared these results to those from studies using modeling approaches to map ES. The former provides knowledge of the current understanding of processes and the second provides information on the parameters that are currently used to map ES. Given their importance for soil health, we focused our review on the following ES for which forest soils play a critical role: (I) timber production, (II) soil carbon storage, (III) regulation of water flow and provision of clean water, and (IV) the soil as a habitat for organisms (Lehmann et al., 2020).

2 | METHOD AND DATA

We performed a literature search in titles, abstracts, and keywords using Scopus and Google Scholar only retaining peer-reviewed articles having a DOI to ensure findability. For each ES, the search string included a term that described the value of the ES (described below) together with "AND forest AND soil parameters OR soil variables." For timber production, we used the keyword "site index," which is tree height estimated for a standard stand age and represents an index of site productivity. It is widely used in forest management and expresses site productivity without being affected by tree density. We used "soil carbon stocks" for the ES soil carbon storage, the terms "water quality" and "water quantity" for the ES related to the regulation of water quantity and the provision of clean water, and "soil biodiversity" for the habitat service provided by the soil. We excluded studies dealing with highly perturbated sites, such as contaminated sites, which would often not be relevant to mapping. Next, we excluded duplicates and non-relevant records based on the abstract and title. To retrieve further literature sources, we used the snowballing, which involved scanning the reference list of recent papers to identify additional references (Wohlin et al., 2022). A posteriori, we found that a systematic literature search was problematic because the combination of keywords used often did not target studies that were useful to identify soil properties that are related to ES. We relied on papers found with the snowballing approach and expert knowledge, in addition to the ones found with the systematic literature search. In addition, when one or several recent reviews on the topic existed, these studies were used in lieu of a new literature search to avoid replicating the effort. This was particularly true for soil carbon storage, for which several recent reviews were found (e.g., Deluca & Boisvenue, 2012; Wiesmeier et al., 2019). A limitation of this study is that not all studies considered examined the same set of variables. This implies that when a variable is not selected in a given study, it was either not assessed or it was not related to a specific ES and we could not distinguish between these two possibilities. However, when a parameter was identified as a driver of an ecosystem process, it is a true positive and it does represent a relationship between the two variables. Another limitation is that identified variables are not necessarily causal. They can be correlated with other variables that are implicated in the processes responsible for delivering the ES.

We categorized the results according to the physical, chemical, and biological soil parameters. We used all soil properties identified as mandatory in *GlobalSoilMap* (see Box 1), and we added a few properties that were found frequently in studies linking soil properties to ecosystem function and services. The properties considered were the following: physical properties (structure, soil type, stone content, bulk density, texture, horizon depth, soil depth, air capacity, available water capacity, hydromorphic properties, saturated hydraulic conductivity, and percolation rate); chemical properties (pH, soil organic carbon [SOC], cation exchange capacity (CEC), base saturation (BS), nitrogen (N) either total, mineral, or mineralization rates, exchangeable potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), manganese (Mn), extractable phosphorus (P), and Al and Fe oxides); and biological properties (humus thickness or type [mull, moder, mull], soil fauna, and coarse woody debris). For convenience, soil type was categorized in the physical soil property group, because of the dominant effect of landform and soil texture on soil types, but we recognize that soil profile development across the globe is the result of the five soil-forming factors as outlined by Jenny (1994): relief/topography, climate, parent material, biota, and time. Humus was placed in the biological category by convenience and due to the importance of the biota (soil fauna and vegetation composition) in shaping this layer.

3 | RESULTS AND DISCUSSION

3.1 | Site productivity

The literature search yielded 78 documents, out of which 65 were found relevant to our study by linking soil properties to forest productivity. The list of references can be found in Supporting Information 2. A large portion of the studies (82%) included at least one physical soil parameter to predict forest productivity and an equally high number of studies included at least one chemical parameter (85%), while only 12% of the studies included biological parameters (Figure 3). Of the studies that used physical soil properties, a large proportion (83%) found that by adding one or more chemical parameters enhanced the quality of the prediction. Soil texture was by far the property the most often selected (51%) followed by soil depth (25%), whereas soil pH was the chemical soil parameter the most often selected (49%) followed by soil organic matter (SOM) content (40%), CEC (30%), various metrics expressing N availability or content (25%), and BS (17%). Biological soil properties, including humus depth and soil fauna, were found to be related to site productivity in only 6% of the studies.

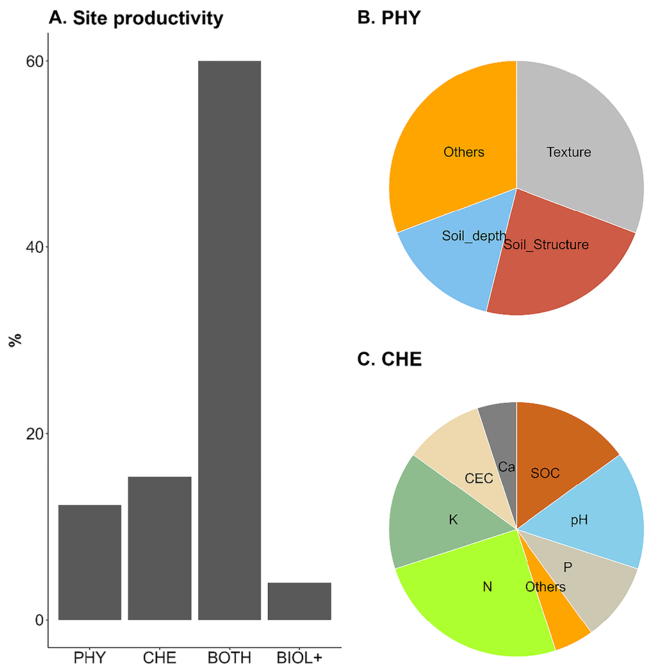

FIGURE 3 (A) Parameters used to predict site productivity in empirical studies. Proportion of studies using at least one soil physical properties and no chemical properties (PHY), proportion of studies using at least one soil chemical properties (CHE) and no physical properties, and proportion of studies using both soil physical and chemical properties (BOTH). Studies using biological soil properties (BIOL+) were always accompanied by either PHY or CHE properties. (B) Relative importance of individual physical parameters and (C) relative importance of individual chemical parameters. CEC, cation exchange capacity; SOC, soil organic carbon.

Several studies have revealed that the contribution of soil parameters to predicting forest productivity is context dependent. For example, Oddi et al. (2022), in Patagonia (Argentina), found that once terrain and climate are considered, soil added 7% to the explained variability. Messaoud et al. (2022) highlighted that the soil C:N ratio can be an important contributor but only for some tree species in northwestern North America. Sewerniak (2020) found that productivity estimates that included soil variables were only important for nutrient-poor soils, in this case podzols, for Scots pine in Central Europe. Scheepers and Du Toit (2020) suggested that only the soil parameters that related to water availability contributed significantly to explain forest productivity for an arid region of South Africa. Pinno and Bélanger (2011) highlighted that specific soil properties contributed to explaining the productivity of aspen trees in Canada, but that these properties varied with soil type. Finally, in contrast to upland soils, a study conducted on forested wetlands found that none of the soil parameters assessed contributed to explaining spruce productivity under boreal mire conditions in Poland (Bijak, 2017).

Altogether, these studies indicate that soil parameters can improve the prediction of site productivity. A global analysis revealed that soil nutrient availability increases the proportion on net primary production (NPP) to gross primary production (GPP) (Fernández-Martínez et al., 2015). Because GPP is widely available from remotely sensed data, this study stresses the importance to map soil parameters, including pH, nitrogen, potassium, and phosphorus, to improve the mapping of forest productivity and to better estimate global terrestrial carbon sequestration. Another global scale study (Hanson et al., 2020) indicated poor linkages between soil nutrient pools and concentrations with forest productivity. A companion study of this latter one (Legout et al., 2020) suggested that ecosystems relying on large geochemical influx by atmospheric inputs, capillary rise, or intense mineral weathering may have a high productivity while showing low soil nutrient reserves. These studies suggest that soil nutrient status may not always reflect site productivity and that biogeochemical cycles should also be considered in addition to basic soil assessment. Soil nutrient availability is part of the equation, but other properties, including mineralogy or aridity, are important drivers of nutrient fluxes that need to be considered.

Overall, our analyses revealed that the consideration of soil variables can significantly improve the prediction and mapping of forest productivity. In many cases, the consideration of soil chemical properties, in addition to physical soil properties, improved the quality of the predictions. Nevertheless, the relationships found between soil variables and forest productivity cannot be universally applied, and the consideration of soil variables within a stratification framework by variables such as drainage, soil types, or geochemical inputs could make these relationships clearer.

3.2 | Soil organic carbon storage

The literature search generated 134 results. However, most of these studies have investigated the linkages between SOC stocks with either remote sensing data, forest composition, land use change, disturbance, or topography and were not retained for the present study if they did not include any soil physical, chemical, or biological variables. Only 23 studies were kept (Table S3). Many studies have developed predictive models based on remote sensing without using any soil information other than the predicted variable, SOC content. However, several studies have indicated that the predicting performances of DSM for drivers of SOC content, including texture and soil pH, are generally better than that of SOC content (Beguin et al., 2017; Chen et al., 2022; Mansuy et al., 2014). Also, the mapping of drivers of SOC storage may be more useful than that of SOC stocks to evaluate the potential for additional sequestration or the potential for losses of SOC with disturbances. For example, Ouimet et al. (2023) identified soil texture as a major determinant of the response of SOC to harvest residue retention, while Nave et al. (2022) found that soil texture, profile depth, soil parent material, and forest cover were the strongest predictors of harvest impact on SOC.

Physical soil properties were found to be useful in predicting SOC storage in most studies (61%). Chemical properties were found to be successful predictors in 52% of the studies, while only 22% of the studies selected both physical and chemical properties and only 9% of the studies selected biological soil properties (Figure 4A). Texture, soil type, pH, and nitrogen were the soil properties that were the most often selected. The recent review of the drivers of SOC storage conducted by Wiesmeier et al. (2019) revealed that different parameters come to play at different scales. While silt and clay content were good predictors of SOC content for a wide range of scales, ranging from <1 m^2 to 1 M km^2, other properties, including cations availability, Fe and Al as well as aggregate content, were important drivers at micro to local scales. The large proportion of studies that identified only physical properties or only chemical properties as drivers of SOC stocks may indicate that studies were conducted at different scales or that the study design was focused on one type of properties. Among the biological soil properties, humus type was selected in one of the 23 studies kept in the literature search (Table S3).

3.2.1 | Process-based modeling SOC storage

Many models were developed to predict SOC stocks. While most are designed for agricultural lands, they often can be adapted to forest soils. At least three reviews have discussed the data requirements and the processes represented by such models (Dai et al., 2019; DeLuca & Boisvenue, 2012; Peltoniemi et al., 2007) and a summary is presented in Table 1. This compilation reveals that several models do not use any soil parameters to predict SOC stocks. In models that are using soil properties, clay content, organic matter (OM), bulk density, and coarse fragment are useful to represent

TABLE 1 Parameters used in models predicting soil C stocks (from the reviews of Deluca and Boisvenue [2012] and Peltoniemi et al. [2007]).

Models	Parameters	References
Yasso	No soil information, litter quality	Liski et al., 2005
Century	Texture, C:N	Parton et al., 1993
Romul	Texture, biota	Chertov et al., 2001
RothC	Texture	K. Coleman et al., 1997
BiomeBGC	No soil information requirement	Thornton, 1998
Smart2	Soil acidification, soil biota	Kros et al., 2002
Ecosys	Water, temperature, soil biota	Grant et al., 2006
Forecast	Litter decay	Kimmins et al., 1999
CBM-CFS3	No soil information requirement	Kurz et al., 2009
Mimics	Texture, litter chemistry	Wieder et al., 2014
Review of 25 Earth system models	Twenty-two used texture or soil water characteristics Three used soil organic matter One used soil color class and one used soil albedo	Dai et al., 2019

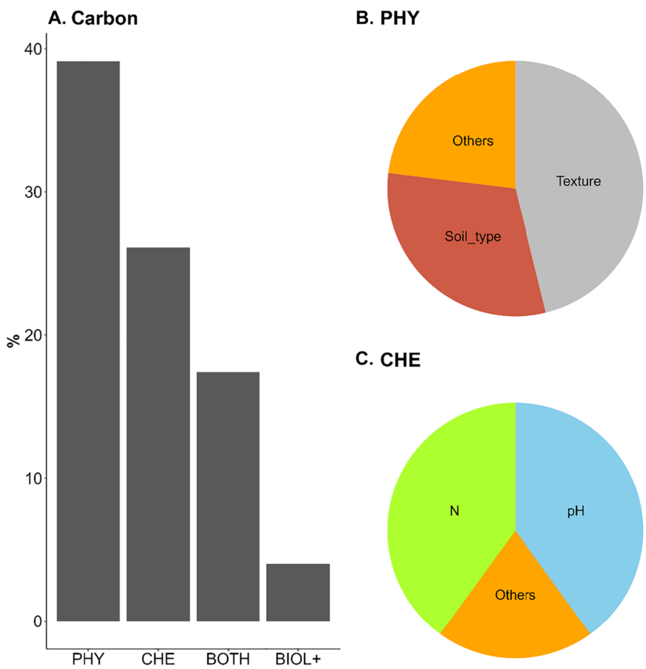

FIGURE 4 (A) Parameters used to predict soil organic carbon (SOC) stocks in empirical studies. Proportion of studies using at least one soil physical properties and no chemical properties (PHY), proportion of studies using only soil chemical properties (CHE) and no physical properties, and proportion of studies using both soil physical and chemical properties (BOTH). Studies using biological soil properties (BIOL+) were always accompanied by either PHY or CHE properties. (B) Relative importance of individual physical parameters and (C) relative importance of individual chemical parameters.

thermal and hydraulic characteristics which drive many soil processes (Dai et al., 2019).

Most models are strongly driven by NPP (litter inputs) and litter quality. H. Zhang et al. (2020) noted that first-order models like CENTURY assume a linear relationship with productivity and SOC stocks and showed that the simulated SOC concentrations from CENTURY and MIMICS models are systematically biased from observations along the gradients of local litterfall production. These results are in line with an increasing number of experimental studies showing that litter input rates and sources are not as good predictors of soil carbon stocks as previously believed (Lajtha et al., 2018). These biases were attenuated with the use of models that consider microbial turnover. They also indicated that biases were correlated with soil properties including bulk density (for all models), CEC, pH, and BS. This observation suggests that soil properties could help with improving model predictions especially when difficult to obtain microbial properties are not available.

Changes in SOC stocks result from the difference between C inputs by plant photosynthesis and OM decay rates. Studies using litter addition with isotopic tracers have found that a large portion of added C is lost within a few years (Janzen et al., 2022). A change in input rates is therefore likely to cause changes in the labile, active, or young SOC reservoir. The resistant SOC, however, makes the bulk of SOM and the factors that control it are of great interest. Schmidt et al. (2011) illustrated that persistent SOC is not necessarily refractory SOM. It is made of OM that resists decay because of various processes including protection from microbial processing within soil aggregates, chemical bounding of SOC with metals, or simply the lack of accessibility to decomposers by waterlogged, dry, or cold conditions. Persistent SOM originates both from microbial processing (Kögel-Knabner, 2017) and from stabilized plant-derived compounds (Angst et al., 2021). Models of the Century type (Parton et al., 1993) use soil texture (silt and clay fraction) to define the capacity of soil to sequester C. These models predict slower SOM turnover and higher SOM storage in fine-textured soils. However, recent work has shown that the composition of silt and clay matters, specifically its metal oxides content which can importantly change the capacity of soil to sequester C (Georgiou et al., 2022; Heckman et al., 2018; Rasmussen et al., 2018). Several studies have shown that soil mineral composition has a more significant effect than soil texture on SOC stocks and sorption (Kothawala et al., 2009; Rasmussen et al., 2018). Using a large database from almost 63000 pedons, Rasmussen et al. (2018) found that clay content had a relatively small explanatory power, while exchangeable Ca was a strong predictor of SOM content in moisture-limited alkaline soils, and Al and Fe oxyhydroxides were the best predictors in acidic soils. These results indicate a need to adapt biogeochemical models to include key drivers and to better map these soil drivers of SOM accumulation including metal oxides and exchangeable cations.

3.3 | Water quantity and quality

Critical water-related ES provided by forest soils are streamflow regulation, which can reduce downstream flood and water scarcity risks, and the provision of high-quality freshwater supporting healthy aquatic ecosystems and reducing drinking water treatment costs (Neary et al., 2009). Forest soils are important to these ES because soils control the storage and release of water and solutes to stream networks. In addition, soils can be the key medium through which water travels from the time it enters a watershed as precipitation to when it exits as streamflow (Botter et al., 2010).

Linking soil properties to water-related ES can be difficult due to scaling challenges. Soil properties and digital soil maps are typically resolved at the point or pedon scale. In contrast, stream water quantity and quality are a product of both pedon-scale and hillslope-scale to catchment-scale processes. For example, stream water quality may be primarily dictated by processes occurring within riparian soils, regardless of the soil pathways water travels before entering the riparian zone (Laudon et al., 2011; Ploum et al., 2021). Similarly, temporal scales must be considered since hydrologic processes are dynamic at event (e.g., rainfall and snowmelt), seasonal, and interannual scales; however, most DSM products represent a discrete period.

The need to integrate both spatial and temporal dynamics of water storage and movement to understand soil–water interactions has led to the development of frameworks such as the variable source area concept (McDonnell, 2009). The variable source area concept highlights that parts of the landscape that contribute to streamflow (and hence stream water chemistry) are dynamic through time (Bernier, 1985; Walter et al., 2000). This spatiotemporal complexity creates significant scaling challenges when linking soil properties derived from DSM to water-related ES. Despite challenges associated with resolving spatiotemporal dynamic water quantity and quality metrics with static, point-scale soil information, there are key pedon-scale properties that are known to influence these ES. The importance and complexity of the spatiotemporal phenomena linking soil and water properties prevented us from using the same systematic literature review approach as that used for the other sections; therefore, a traditional synthesis based on expert knowledge was used. In the following sections, we briefly discuss concepts and soil properties that influence three aspects of water quality and quantity: streamflow regulation, water temperature, and solute chemistry.

3.3.1 | Streamflow regulation

Processes within forest soils can regulate streamflow magnitude and timing by storing water, diverting water to the atmosphere through evapotranspiration, and influencing water flow pathways and thus the time it takes precipitation to reach the stream (Buttle, 2006; McDonnell et al., 2018). Key soil properties that are related to these processes include soil depth, texture, bulk density, hydraulic conductivity, and rooting depth (Vereecken et al., 2015). Soil depth, texture, and bulk density are related to the potential water storage capacity of the soil (Hümann et al., 2011; Seyfried & Wilcox, 2006). Catchments with soils that have greater water storage capacity tend to have augmented low flows and lower magnitude floods compared to catchments with soils that have low water storage capacity (Buttle, 2006). In addition, depth to bedrock or compacted till can be useful information for understanding and modeling subsurface flow paths, as the bedrock or till elevation can have an overriding influence on subsurface water routing in comparison to the role of surface topography (Freer et al., 2002; Hutchinson & Moore, 2000). Water travel times within soil will be related to transmissivity and hydraulic conductivity, which are influenced by soil texture and bulk density. Water travel times along hillslopes can have implications for streamflow timing, but also for water quality (Leach et al., 2020; Li et al., 2021). Rooting depth is also a critical soil characteristic that can influence streamflow regulation as it dictates the extent of water available to vegetation and water partitioning between evapotranspiration and runoff to streams (McCormick et al., 2021). Evapotranspiration of soil water can decrease the amount of water available for streamflow and increase soil water storage capacity. The latter is important when considering soil moisture conditions prior to rainfall events, since a larger soil water storage capacity can reduce downstream high flows (Nijzink et al., 2016). Despite clear conceptual linkages between soil properties and streamflow regulation, the causal processes that generate these relationships are not fully understood and require further research (Gao et al., 2023).

3.3.2 | Water temperature

Water temperature influences aquatic habitat, fish growth, and rates of chemical and biological processing within stream environments (Webb et al., 2008). For these reasons, water temperature is a key parameter for water-related ES, such as the provision of healthy aquatic ecosystems and high-quality drinking water (Delpla et al., 2009; van Vliet et al., 2012). Water temperature can be strongly influenced by energy exchanges at the stream surface, such as incoming solar radiation; however, there has been growing recognition that subsurface inflows to streams can also be an important control on thermal regimes (Leach et al., 2023). As highlighted above, the magnitude and timing of water entering streams, which influence stream temperature through advective exchange, can be strongly related to certain soil characteristics, such as soil depth, texture, and bulk density (Leach & Moore, 2017). In addition, soil properties that influence thermal conductivity, such as bulk density and OM content, will influence soil temperature, which in turn, will dictate the temperature of subsurface water before it discharges to the stream (Kurylyk, MacQuarrie, & McKenzie, 2014). The physics behind soil water and heat exchange processes, within the context of stream temperature, is relatively well understood and this understanding has been incorporated in various physically based models (Kurylyk, MacQuarrie, & Voss, 2014); however, data to parameterize soil characteristics in these models are often lacking, which has necessitated the use of conceptual models that simplify many of these physical processes (Leach et al., 2023). A potential opportunity for DSM is to provide the necessary soil characteristics to apply physically based subsurface water and heat models over larger spatial scales.

3.3.3 | Solute chemistry

Stream water chemistry is the product of soil–plant–atmosphere and groundwater–surface water interactions (Grathwohl et al., 2013). In undisturbed forested catchments, water chemistry is influenced by several factors, as reported by Finér et al. (2004), including atmospheric inputs, weathering, mineral soil reactions, and biological processes such as litterfall and the decomposition of OM. In particular, temperature and hydrological conditions can have significant effects on these processes and their interactions.

While bedrock chemistry is important for predicting stream water chemistry during baseflow conditions (Olson & Hawkins, 2012), the role of soil chemistry and catchment hydrology in controlling stream water chemistry is widely recognized (Billett & Cresser, 1992). Various field investigations have shown that the spatial heterogeneity in physical and chemical properties of soils on hillslopes may play a central role in the determination of water quality (e.g., Billett & Cresser, 1992; Chappell & Ternan, 1992; Hill, 1990; Mulder et al., 1995). These soil properties, along with vegetation and topography, are major factors controlling landscape hydrology and biogeochemical dynamics; however, their relative importance can vary locally and regionally (Ma et al., 2017).

Understanding the concentration of different soil elements and compounds (e.g., nitrogen, sulfur, phosphorus, OM content and composition, cations, anions, and metals) is one of many important factors that regulate streamwater chemistry. Knowing how tightly these elements and compounds are bound to the soil matrix (e.g., sorption capacity and ion exchange capacity), and under what conditions they can become mobilized (e.g., oxidation–reduction state and pH) and/or mineralized (temperature-dependent reactions) is also key (Essington, 2015). These concentrations and conditions are influenced by soil depth, soil texture, surficial geology, forest floor depth and vegetation composition, as well as soil physical environmental conditions, such as moisture and temperature.

Although links exist between surface water chemistry and soil distribution, the dominant soil types on an area basis do not necessarily control sub-catchment hydrochemistry (Stutter et al., 2006). Instead, contributions from small but disproportionately influential source areas (e.g., Kirchner et al., 1993) or along flow paths (Billett & Cresser, 1992) can be largely responsible for the chemical signal of the streamwater. For example, Stutter et al. (2006) found a small tributary (3% of total area) close to the outlet was influential in controlling the overall outflow chemistry from the whole catchment. Others have shown that the riparian zone (Lidman et al., 2017; Smart et al., 2001) or saturated Gleysols and Histosols soils (e.g., Christophersen et al., 1990) are critical areas to determine stream water chemistry at watershed scales.

Changes in streamwater chemistry over time (e.g., between periods of low and high flow) can be explained by changes in hydrological pathways in upland soils (Bishop et al., 1990; Mulder et al., 1990). A recent paper by Knapp et al. (2022) provided a unifying conceptual understanding. Their work showed that both lateral and vertical distributions of solutes need to be integrated and considered together with the temporally variable hydrologic connectivity of these lateral areas to the stream when assessing streamwater chemistry. Variations in solute concentrations in streams are assumed to be largely controlled by the vertical distribution of the solutes in the soil. The concentration of solutes derived from bedrock typically dominates under dry conditions when the groundwater is the primary contributor to streamflow, but this bedrock influence can decrease with increasing stream discharge (Neal et al., 1990; Stewart et al., 2022; Zhi et al., 2019). Conversely, the concentration of solutes derived from the upper mineral and organic soil layers increases under wetter conditions, because these layers increasingly contribute to streamflow during high-flow conditions (Herndon et al., 2015; Neal et al., 2012). Lateral source distribution for solute export patterns has also been widely recognized, with the lateral distribution of source and their topographic position controlling streamflow concentration for dissolved organic carbon (DOC) (Boyer et al., 1997) and nitrate (Vidon & Hill, 2004).

Another important metric of water quality that has received significant research attention is dissolved organic matter ([DOM], often measured as DOC). DOM is a source of energy in stream ecosystems (Hope et al., 1994; Wetzel, 1992) and has an important role in many chemical processes within streams, including complexation and mobilization of metals and formation of disinfection byproducts, which can affect drinking water quality (Kritzberg et al., 2020). Streamwater DOC concentrations are determined by several factors within the soil environment, including the rate of DOC production in organic soils, adsorption of DOC in mineral soils, and the flow path of water through different soil horizons. Many studies have shown that stream water DOC concentration can be related to the amount of wetland present, particularly in small upland headwater catchments (e.g., Creed et al., 2008; Hope et al., 1997). However, at larger scales, riverine DOC fluxes can be related to the size of the SOC pool in the catchment and may be the single most important determinant of the amount of DOC transported out of catchments (Aitkenhead et al., 1999). Recently, a global review indicated that boreal and temperate forests were the regions generating the greatest amount of DOC (Guo et al., 2020) and found several soil properties associated with high DOC content in porewater, including soil temperature, soil water content, sand and clay content, total soil carbon content, total nitrogen, and bulk density. This suggests that estimates of soil properties, and especially soil carbon content, could be used to predict mean stream water DOC concentration over a range of catchment scales, provided that soil data are available at a sufficiently detailed scale. Recent studies are also highlighting the importance of soil processes in shaping the molecular structure of DOM (Freeman et al., 2024), with further implications on stream ES, including productivity and carbon cycling (Kaplan & Cory, 2016).

Understanding how hydrological processes in soils integrate to control runoff generation and solute transport at the catchment scale is still poorly understood (Laudon et al., 2007; McGuire & McDonnell, 2006) and is extremely variable between different geographical regions (Tetzlaff et al., 2009). However, the ecohydrological importance of soils and their spatial distribution in controlling the catchment hydrological and hydrochemical response is clear (Tetzlaff et al., 2014). Since water quantity and quality ES not only reflect their "sources" on the landscape, but also their connectivity across the landscape in both space and time (Stewart et al., 2022), a more holistic approach beyond examining only pedon-scale characteristics must be applied. Mapped soil properties need to be interpreted within the context of other ecosystem processes (hydrologic flows) and thus will require merging DSM approaches with digital terrain modeling (DTM) or other modeling approaches. This is still an emerging discipline that holds promise as both fields further develop.

3.4 | Habitat

Most papers selected using the keywords string with the term biodiversity generated papers that did not focus on the linkages between organisms and soil properties. We also tried the following terms: "soil biodiversity," "soil biota," "niche," "rare species," and "hotspot," which generated similar results. Most studies targeted effects of disturbance on organisms or effect of organisms on soil properties. We relied on highly cited papers and used the snowballing approach as well as on expert knowledge and on the few studies considered pertinent in the literature search. We acknowledge that a lot of pertinent studies may have been missed using this approach, but with a limited number of studies in hand, we found a certain consistency in the soil parameters that were identified as important for qualifying soil as a habitat. Thirty-four studies were used. They investigated organisms in different combination from microbes, soil invertebrates, to plants (Supporting Information 4).

The literature search indicated that chemical soil properties as well as a combination of physical and chemical soil properties were useful in explaining the distribution of organisms. Among the chemical parameters, soil pH was by far the most frequently selected parameter for a variety of organisms from plants to microorganisms and at various scales, from local to continental scales (Supporting Information 4). Nitrogen (either content, concentrations, mineral N, or mineralized N), which is related to forest productivity, was the second chemical parameter to be selected. Among the physical properties, soil texture and soil types were the most frequently selected parameters (Figure 5). Among the soil biological properties, coarse woody debris was found as a useful predictor of arthropod diversity (Table S4).

Soil is the most complex habitat on earth (Voroney & Heck, 2015) and has been estimated to be home to 59% of life, making it the most biologically diverse habitat (Anthony et al., 2023). Soil is an important habitat for plants, vertebrates, invertebrates, and soil microorganisms. There are numerous drivers for the distribution of organisms, but soil properties provide an environmental filter that defines the potential of a site to support selected biota. This is most evident with trees and understory vegetation cover (Oddi et al., 2022; Skovsgaard & Vanclay, 2013). Soil properties such as pH, soil nutrient availability, and water availability are also important factors that drive plant species composition (Bartelheimer

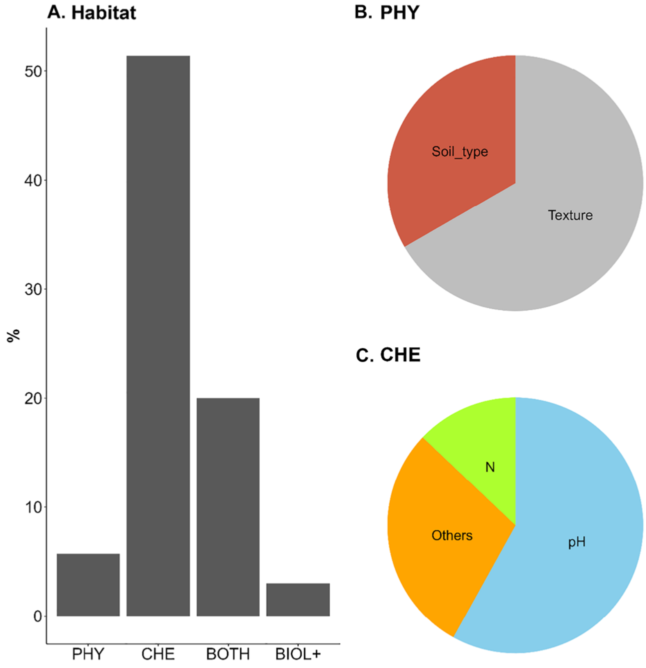

FIGURE 5 (A) Parameters used to predict the distribution and abundance of organisms in empirical studies. Proportion of studies using at least one soil physical properties and no chemical properties (PHY), proportion of studies using only soil chemical properties (CHE) and no physical properties, and proportion of studies using both soil physical and chemical properties (BOTH). Studies using biological soil properties (BIOL+) were always accompanied by either PHY or CHE properties. (B) Relative importance of individual physical parameters and (C) relative importance of individual chemical parameters.

& Poschlod, 2016). These soil–plant relationships are represented in many forest classification systems that interpret forest classes in relation to axes of moisture and nutrient richness in edatopic grids (Sims et al., 1989). In fact, indicator plant species are often used to interpret the nutrient regime of a site (Diekmann, 2003).

The value of soil as a habitat for living organisms is generally assessed through the analysis of its biodiversity, which is both difficult to define and to measure. Leeuween et al. (2019) defined soil biodiversity function as "the multitude of soil organisms and processes, interacting in an ecosystem, providing society with a rich biodiversity source, and contributing to a habitat for aboveground organisms." As highlighted by the authors, there is currently no single measure reflecting simultaneously the diversity of soil organisms and its capacity to support a diverse ecosystem. Nevertheless, as indicated in this review, several soil parameters are linked to richness, community structure, and/or soil biotic community assemblages both at local and global scales. Therefore, grided maps of soil properties should be useful to reflect some foundational properties that support soil biodiversity. As an example, significant relationships were found between bacterial beta-diversity (i.e., a descriptor of community structure and composition) and soil properties, including pH, in a dataset of 76 soils from various land use types (Griffiths et al., 2016). In a following step, this study used soil pH to predict soil bacterial biodiversity across Europe (Griffiths et al., 2016). While pH maps were found useful for predicting extreme habitat conditions for biodiversity, their predictive value was limited for some regions and soil types (e.g., organic/acidic soils), suggesting that the use of more accurate maps and considering additional soil properties could increase the accuracy of the predictions (Griffiths et al., 2016). In another study, multiple soils properties (pH, soil texture, and SOM) and environmental parameters (potential evapotranspiration, average temperature, soil biomass productivity, and land use type) were combined using scores associated to threshold values for each variable to predict and map the soil habitat potential for biodiversity across Europe (Aksoy et al., 2017). Validation of model predictions using an earthworm dataset, however, showed limited success (Aksoy et al., 2017). Adding biological properties did not significantly improve the model (Rutgers et al., 2019), indicating that generating combined soil biodiversity and soil properties datasets at broad scales might be necessary to develop efficient predictive tools for soil biodiversity, especially in northern latitudes where the data coverage is poor or discontinuous (Cameron et al., 2018).

There are several complicating factors in predicting soil biodiversity from soil properties. The first is the large fine-scale spatial heterogeneity of soil properties (e.g., pH, OM, P, N, and aggregate distribution) and of soil communities (Dumbrell et al., 2010; Ettema & Wardle, 2002; Nielsen et al., 2010), making it complex to choose the appropriate resolution for soil habitat mapping. In addition, there is considerable unexplained variance in the relationship between soil properties and soil community distribution which may be in part due to dispersal limitation of soil organisms (Caruso et al., 2012; Lindo & Winchester, 2009). Another complicating factor is that soil organisms also create their own soil environment. The role of plants in shaping soil conditions is well illustrated in common garden experiments (Steffens et al., 2022). Soil organisms also modify the soil in which they live (D. C. Coleman et al., 2004). Therefore, it is difficult to separate the idea of soil habitat from the soil organisms themselves. Finally, a dominant role is played by non-soil factors in shaping species habitat (Figure 2; natural drivers). For example, disturbances, climate, and, importantly, the full living community with interaction and competition relationships (Land & Benbow, 2013) are major drivers of species presence and abundance and of the community composition of organisms depending on the soil as their habitat. The static or inherent soil properties (see glossary in Supporting Information 1) are useful to define the potential suitability of the habitat, the limits (thresholds), or the optimal conditions for a species or a community, while manageable properties (see glossary in

Supporting Information 1) are useful in defining the quality of the soil in its current state. Our literature search revealed that some properties seem to have a strong influence both at the local and global scales. In particular, soil pH and water availability appear to be major factors that shape species habitat suitability and community composition (Table S4).

Already, several studies, including the ones discussed in this section, have used digital maps of soil properties to improve the mapping of soil biodiversity. These studies, and the results presented, here, indicate the value of improved DSM to assess and map biodiversity. These studies, as well as others (e.g., Zuquim et al., 2023), stress the need for accurate maps of relevant soil properties to improve the understanding of the spatial distributions of species and communities and to provide relevant information for conservation planning and sustainable forest management. Digital soil maps have already proven to be useful in predicting future plant distribution under climate change (Ni & Vellend, 2024).

4 | CONCLUSIONS

The idea for this review arose from the observation that grided maps of soil properties are rarely used by land managers to assess ES on forested land, whereas there is an abundance of scientific literature documenting the linkages between soil properties, soil functions, and ES. Currently, the assessment of ES generally relies on ecological land classification with several drawbacks including the nonindependence of soil properties within a polygon, the lack of the appreciation of parameters variability both within and between polygons, and most importantly the difficulties in using the new findings on the linkages between soil properties and soil functions in the assessment of ES. Soil information is generally used qualitatively to evaluate ES and make forest management decisions. Using DSM to appreciate and map ES would lead to greater use of quantitative relationships between soil and ES. This would result in an improvement in the assessment of ES and, above all, in a more direct applicability and link of science with ecosystem management.

Our review revealed the abundance of linkages between soil properties and the ES of timber production, soil carbon storage, regulation of water flow/quality, and as a habitat for organisms and suggest that the use of DSM could improve the assessment of ES and help to better understand their relationship with soil properties. The parameters that are identified as mandatory in *GlobalSoilMap*, which are the most frequently available in DSM products, were found to be useful predictors of ES. The review has identified several challenges in implementing the use of DSM to assess ES as well as several opportunities.

Challenges are as follows:

1. DSM is data intensive and requires appropriate and homogenized covariates to create meaningful models. Limited data in the training set can particularly increase uncertainties in model results and can be misleading if misinterpreted (Bulmer et al., 2019). Additionally, the need for access to a large data set and computational skills remains a barrier compared to conventional soil surveys.
2. Finding the proper scale: Certain soil functions operate at a very small scale, in particular microbial processes, while others operate at a scale that is more common in forest investigations, from the plot (e.g., 0.25 ha) to the polygon (several hectares), while water quantity and quality aspects need to be considered at the hillslope to watershed scales. Finding the right scale may impact on the parameters that come into play. The appropriate scale of the final product should be relevant to the question/application being sought. The coarse scale might be suitable for some applications.
3. Availability of maps for specific parameters: Several soil parameters are often not available at a pertinent scale. For example, among the recommended GlobalSoilMap properties, good quality maps of soil depth and nutrients are rarely available. Moreover, our review highlighted that other properties that are not yet rated as mandatory in global soil mapping initiatives could be useful, including metal oxides concentrations, humus depth and types, as well as other soil biological indicators which have rarely been mapped.
4. The assessment of water ES requires a watershed-scale perspective and recognizes that areas within the watershed may have disproportionate contributions to water flow and chemistry (i.e., hot spots).
5. Some parameters are stable (e.g., soil texture), while others can change with time. Capturing these changing properties represents a challenge for DSM because additional data to track these rapid changes may be lacking. The review highlighted that the linkages between soil properties and ES are complex and that there is no one size that fits all situations. Some parameters come to play in different contexts and at different scales.

Opportunities are as follows:

1. Studying the relationships between soil properties and ES on a local or large scale could uncover new relationships and lead to discovery.
2. Considering and using DSM products to assess ES could effectively link new findings into the forest management practice.
3. Uncertainty in the maps that are created is a useful indication that is not available in traditional maps and that helps in applying/interpreting the maps.

4. Considering and using DSM products to assess ES in relation to soil security could effectively promote the role of soil sustainable management for achieving the SDGs (Bouma, 2019). In the face of interrelated global issues, such as climate change, land degradation, food and water security, the role and capability of DSM will undoubtedly increase, and products will adapt to support policy-makers and land managers (Arrouays et al., 2020).

AUTHOR CONTRIBUTIONS

David Pare: Conceptualization; data curation; formal analysis; funding acquisition; supervision; writing—original draft. **Fidele Bognounou**: Conceptualization; data curation; formal analysis. **Erik J. S. Emilson**: Conceptualization; writing—original draft. **Jerome Laganiere**: Conceptualization; writing—original draft. **Jason Leach**: Writing—original draft. **Nicolas Mansuy**: Conceptualization; writing—original draft. **Christine Martineau**: Conceptualization; writing—original draft. **Charlotte Norris**: Conceptualization; writing—original draft. **Lisa Venier**: Conceptualization; writing—original draft. **Kara Webster**: Conceptualization; writing—original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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