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Effect of spatial scale of soil data on estimates of soil ecosystem services: Case study in 100 km^2 area in France

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Abstract

Over the last decade, the ecosystem services (ESs) framework has been increasingly used to support mapping and assessment studies for sustainable land management purposes. Previous analysis of practical applications has revealed the significance of the spatial scale at which input data are obtained. This issue is particularly problematic with soil data that are often unavailable or available only at coarse scales or resolutions in various part of the world. In this context, four soil-based ecosystem services, namely biomass provision, water provision, global climate regulation, and water quality regulation, are assessed using three conventional soil maps at the 1:1,000,000, 1:250,000 and 1:50,000 scales. The resulting individual and joint ES maps are then compared to examine the effects of changing the spatial scale of soil data on the ES levels and spatial patterns. ES levels are finally aggregated to landforms, land use, or administrative levels in order to try to identify the determinants of the sensitivity of ES levels to change in the scale of input soil data. Whereas the three soil maps turn out to be equally useful whenever ESs levels averaged over the whole 100 km^2 territory are needed, the maps at the 1:1,000,000 and 1:250,000 induced biases in the assessment of ESs levels over spatial units smaller than 100 and 10 km^2, respectively. The simplification of the diversity and spatial distribution of soils at the two coarsest scales indeed resulted in local differences in ES levels ranging from several 10 to several 100%. Identification of the optimal representation of soil diversity and distribution to obtain a reliable representation of ESs spatial distribution is not straightforward. The ESs sensitivity to scale effect is indeed context-specific, variable among individual ESs, and not directly or simply linked with the soil typological diversity represented in soil maps. Forested and natural lands in the study area appear particularly sensitive to soil data scales as they occupy marginal soils showing very specific ESs signatures.

KEYWORDS

ecosystem services, mapping, soil-based ecosystem services, spatial scale

1 | INTRODUCTION

The ecosystem services (ESs) framework has attracted considerable interest among scientists and decision-makers during the last decades because of its potential suitability for both heuristic and operational purposes (Andrew et al., 2015; Baveye et al., 2016, 2021; de Groot et al., 2010; Maes et al., 2012) and it can be viewed as a "bridge between sciences and policy" (Crouzat et al., 2015; Grêt-Regamey et al., 2017; Le Clec'h et al., 2019; Palomo et al., 2018). Indeed, even though considerable progress remains to be achieved concerning the actual measurement of soil ESs in the field (Baveye et al., 2016, 2021; Chalhoub et al., 2020) before the usefulness of ESs framework can be fully ascertained, one might argue that preliminary assessment and mapping based on estimated soil ESs may already be helpful at this stage for a wide range of applications such as spatial planning, climate adaptation and hazard mitigation, conservation or restoration planning (Wang et al., 2020), and corporate risk management (Hamel & Bryant, 2017). ESs mapping is more specifically intended to highlight the spatial variability and potential mismatches of ESs supply and demand, to identify and locate spatial trade-offs and synergies among multiple ESs or, to characterise ESs drivers (Burkhard & Maes, 2017; Crossman, 2013; Englund et al., 2017; Fossey et al., 2020; Schulp et al., 2014). Moreover, maps are frequently used by decision-makers in various planning activities, so that their usefulness to support governance and management of socio-ecological systems is widely recognised (Bagstad et al., 2018; Englund et al., 2017). For all these reasons, ESs mapping has been the object of increasing interest in the past few years by both scientists and decision-makers (Andrew et al., 2015; Directorate General for the Environment, 2018; European Commission, JRC, 2020).

For the purposes of this article we will refer to "scale" as the ratio of a distance on the map to the corresponding distance on the ground (the larger the scale of the map, the better and finer the features that can be detailed), to "resolution" as the size of one pixel on the ground, and to "spatial level" or "extent" as the size of the space where specific processes take place.

Highlights

- The scale of input soil data has a limited impact on ES levels but strong impact on their location.
- The finest ES map grains achievable with the 1:1,000,000 and 1:250,000 soil maps are 100 and 10 km^2.
- Assessment sensitivity to scale effects is highly variable among ESs and is context-specific.
- In this study, ESs in forested lands are especially sensitive to the scale of input soil data.

To take into account the fact that ecosystem, socio-economic, or political processes occur at and/or across various spatial levels (Lavorel, 2017; Raudsepp-Hearne & Peterson, 2016; Xu et al., 2017), ESs mapping has been carried out for spatial extents ranging from patch (10–10^2 km^2) to global (>10^6 km^2) levels (Martínez-Harms & Balvanera, 2012) and for grain sizes (or spatial resolutions) ranging from <0.01 km^2 to more than 100 km^2 (Malinga et al., 2015). Most of the mapping studies are however conducted at the regional (10^3–10^5 km^2) and national (10^5–10^6 km^2) levels (Malinga et al., 2015; Martínez-Harms & Balvanera, 2012) and with resolutions coarser than 0.01 km^2 (Malinga et al., 2015). Such approaches are adequate for initial, diagnostic ESs assessments (Bagstad et al., 2018) and are helpful to enhance public awareness (Andrew et al., 2015; Beaumont et al., 2017) or to design national or regional policies. However, they need to be combined with approaches involving smaller spatial extents and finer grain sizes to design management strategies for specific landscapes (Bagstad et al., 2018; Baveye, 2017; Lee et al., 2015; Obiang Ndong et al., 2020).

ESs mapping on local and patch levels should ideally be carried out at cartographic scales, that is, at ratios of mapped to real distances, ranging from 1:50,000 to 1:5000 (Gómez-Zotano et al., 2018) or resolutions from 0.001 to 0.00025 km^2 (Chen & Zhou, 2013; Herold et al., 2002; Martínez-Harms & Balvanera, 2012). However, the availability of input data classically used to map ESs at such fine scales or resolutions is strongly limited (Lavorel, 2017). This is particularly the case with soil data that are often unavailable or available only at coarse scales or resolutions in most parts of the world (Lavorel, 2017; Lothodé et al., 2020; Müller et al., 2020; Schulp et al., 2014). For instance, legacy soil maps covering the whole continental France are set at two different scales (i.e., 1:1,000,000 and 1:250,000) with the aim to provide soil data for thematic soil mapping from the national down to the regional level. As they are not designed for fine-scale purposes, these maps are likely too coarse for ESs mapping from patch to local levels (10–10^3 km^2). To overcome such limitation, strong efforts have been made in the last decade to produce digital maps providing a subset of quantitative soil properties with various resolutions from global to regional levels (Lemercier et al., 2022; Mulder et al., 2016; Poggio et al., 2021). Unfortunately, the digital soil maps do not cover the full range of data that may be required to assess soil-based ecosystem services, among which the soil type, the depth of hydromorphic features, the rooting depth, or the bulk density in the methodology developed in Choquet et al. (2021). Legacy soil maps are then frequently used to assess soil functions or services at various scales (Rabot et al., 2022; Therond et al., 2017).

The effect of the scale of input data on ESs mapping is a relatively new but fundamental issue (Liu et al., 2017; Raudsepp-Hearne & Peterson, 2016), particularly in developing countries where data availability may be limited (Bagstad et al., 2018). The few existing studies in this respect (Bagstad et al., 2018; Grêt-Regamey et al., 2014) deal mainly with the scale or resolution of land use and land cover data, which are by far the most available and widely used types of information in ESs assessment and mapping (Andrew et al., 2015). These authors reported substantial but highly variable differences in ESs levels and spatial patterns with scales or resolutions according to the biophysical characteristics of the study areas, the models used to assess ESs, or the service being considered (Bagstad et al., 2018; Grêt-Regamey et al., 2014).

As far as we are aware, no similar studies on the sensitivity of ESs mapping to the scale (for conventional soil maps) or resolution (for digital soil maps) of input soil data have been conducted despite (i) the pivotal role of soil type and soil properties in ESs delivery (Choquet et al., 2021; Dominati et al., 2016); (ii) the limited availability of fine scale soil data and consequently the use of coarse soil data in ESs mapping (Markov & Nedkov, 2016; Ungaro, 2021; Villoslada et al., 2018) and finally (iii) the recognised sensitivity of soil-based ESs indicators (e.g., soil carbon stocks or carbon storage) (Zhang, 2018) to the scale of input soil data.

In this general context, the primary objective of the research described in the present article was to analyse the effect of changing the spatial scale of input soil data on the ES levels and spatial patterns. More specifically, our goal was to take advantage of the soil mapping program carried out on the Saclay plateau in France at the scale of 1:50,000, to examine the effect of extracting soil data from legacy soil maps at three decreasing scales (1:50,000, 1:250,000 and 1:1,000,000) on the levels and spatial patterns of four soil-based ESs: two provisioning services (biomass and water) and two regulating services (global climate and water quality).

2 | MATERIALS AND METHODS

2.1 | Description of the study area

The chosen area for this study is the Saclay plateau (Figure 1a), a peri-urban agricultural landscape in the south-west of Paris. The area covers 104 km^2 among which 65.580 km^2 are natural, forested or cultivated lands (Figure 1b,c). The landscape is composed of a vast plateau encircled at its northern and southern boundaries respectively by the Bièvre and the Yvette rivers. The top of the plateau is covered by aeolian loess sediments (0.5–3 m thick) while plateau edges and slopes are formed of clayey and sandy materials, and valleys are composed of alluvial deposits. Whereas agricultural activities dominate on flat plateau positions, forests dominate the surrounding slopes and the valley, when not urbanised (Figure 1).

2.2 | Soil spatial data

Spatially explicit soil data are obtained from three vector conventional soil maps with different spatial scales (Figure 1d–f). Each soil map presents complex Soil Mapping Units (SMU) composed of a set of several Soil Type Units (STU). The STUs are not spatially delineated but their relative abundances inside each SMU is known. In this study, the three soil maps are equally pre-processed and simplified: only the dominant STU is considered, as suggested by INRA Infosol (2005). Morphological and analytical properties of the dominant soils are extracted from the soil database associated with the soil map at the scale of 1:50,000. Such properties, along with the SMU correspondences among each map scale, are listed in Tables S1 and S2.

The first conventional soil map (S1000), at a scale of 1:1,000,000 is the Soil Geographical Database of France (Figure 1d). This map is part of the European Soil

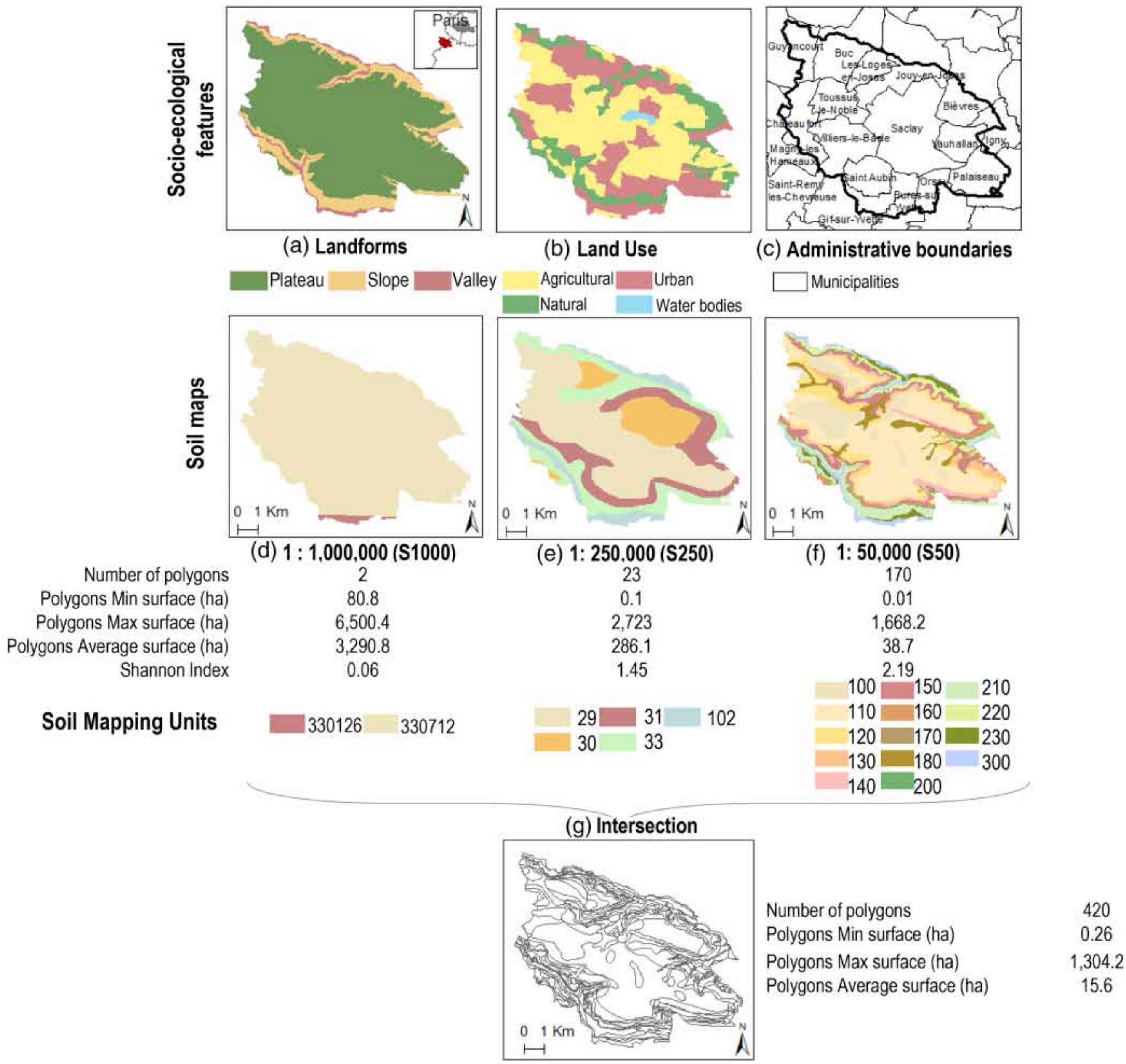


FIGURE 1 Socio-ecological features of the studied area (Saclay plateau) concerning landforms (a), land-use (b) and administrative boundaries (c) and soil maps available for this area respectively at the 1:1,000,000 (d), 1:250,000 (e) and 1:50,000 (f) scales and their intersection (Figure 1g).

Geographical Database of Europe. At such a coarse scale, the Saclay plateau is entirely covered by two different SMUs (Figure 1d). According to the World Reference Base for soil resources (IUSS Working Group WRB, 2015), soils developed in the loess deposit on flat plateau positions were classified as Luvisols (SMU 330712) and those formed in sandy slope deposits as Arenosols (SMU 330126). At this scale, the areas classified as urbanised were reclassified as Luvisol where finer scale soil maps or field observations indicated the absence of artificialised areas.

The second conventional soil map (S250) is at a scale of 1:250,000 (Figure 1e) and is provided by the *Référentiels Régionaux Pédologiques* (RRP), which are the geographic soil databases at the regional level in France (Roque, 2004). The RRP represent the most detailed source of soil information for the whole continental France. Five SMUs were accounted for within the study area. Soils on top positions of the Saclay plateau were classified as Endostagnic Luvisols (SMU 29). When the thickness of the loess deposit decreases and the underlying clayey materials are closer to the soil surface, soils shift to Katostagnic Luvisols (SMU 30). Along the edge of the plateau, Planosols (SMU 31) developed in the superposition of silty loamy slope deposits over clayey materials. Finally, soils encountered on slope areas and in valley areas were classified respectively as Stagnic Cambisols (SMU 33) and Reductic Stagnosols (SMU 102).

The third conventional soil map (S50) is at a scale of 1:50,000 and is the result of a sampling survey carried out in the study area between 2016 and 2018 (Figure 1f). This map is the most detailed source of spatialised soil data in the Saclay plateau. At this scale, 14 SMU are identified: nine on plateau positions (SMUs 100 to 180), four on slope positions (SMUs 200 to 230) and one in the valley (SMU 300). Soils located on the plateau were classified as Haplic Luvisol (SMU 100), Endostagnic Luvisol (SMU 110), Katostagnic Luvisol (SMU 120), Pantostagnic Luvisol (SMU 130), Endoraptic Planosol (SMU 140), thick Epiraptic Planosol (SMU 150) and thin Epiraptic Planosol (SMU 160). These soils are more or less concentrically distributed from the top to the edge of plateau positions as a result of the progressively decreasing thickness of the loess deposit and the exposure of underlying clayey materials toward the borders of the Saclay plateau. When clayey materials are present throughout the soil, soils were classified as Vertic Cambisol (SMU 170) whereas those found in thalweg positions were classified as Stagnic Cambisol (SMU 180). Soils from upslope to downslope positions were successively classified as Skeletic Regosol (SMU 200), Arenosol (SMU 210), Cambisol (SMU 220) and Stagnic Cambisol (SMU 230) as a result of the upslope accumulation of the coarsest colluvic materials and the downslope accumulation of the finest ones. Finally, soils located in valley areas were classified as Reductic Stagnosol (SMU 300).

2.3 | Assessing and mapping the soil-based ecosystem services at different scales

Two provisioning (biomass and water) and two regulating services (water quality and climate) were assessed in each of the 14 dominant soils in the Saclay Plateau according to the empirical modelling approach (Table 1) developed and tested at the 1:250,000 scale in Choquet et al. (2021). The empirical approach was chosen because at this stage it is the only one that is able to deal with the wide diversity of soils observed in the Saclay plateau (Choquet et al., 2021).

The provision of plant biomass was assessed by the suitability of soils to grow winter wheat using the Muencheberg Soil Quality Rating (M-SQR) expert-based tool (Mueller et al., 2007). When agricultural practices are assumed constant as in this study, it seems reasonable

TABLE 1 indicators and empirical models used for the assessment of the four soil-based ecosystem services. Adapted from Choquet et al. (2021).

Ecosystem service	Metric	Unit	Description	Method	Model	Reference
Biomass production	Yield	n/a	Soil suitability to grow winter wheat through Muencheberg Soil Quality Rating	Expert-based scoring	Muencheberg Soil Quality Rating	Mueller et al. (2007)
Water production	Infiltrated water (1 m depth)	n/a	Inherent capability of water to infiltrate through the soil down to 1 m depth	Expert-based scoring	SENSIB	Cam et al. (1996)
Water quality regulation	Non-leached nitrogen	n/a	Non-leached nitrogen	Expert-based scoring	Merlin V2	Aimon-Marie et al. (2001)
Climate regulation	Carbon (C) storage	$g\ C\ kg^{-1}$	Inherent maximum stock of stable organic carbon saturated in the soil	Pedotransfer function	C saturation pedotransfer function	Hassink (1997)

to consider that the variability of yields among soils may be used as a measure of the variability of the soil contribution to plant biomass provision (Choquet et al., 2021). The water provisioning service was defined as the water that is routed to surface water or groundwater bodies (Choquet et al., 2021). This service was assessed by the inherent capability of water to infiltrate through the soil down to one-meter depth using the expert-based scoring tool SENSIB (Aveline et al., 2009; Cam et al., 1996). The regulation of the water quality was assessed by reversing the risk of nitrate leaching ranked in three classes with the MERLIN V2 model (Aimon-Marie et al., 2001; Aveline et al., 2009) for soils under a rapeseed/wheat rotation with high N inputs (168 kg N ha^{-1} for winter rapeseed and 200 kg N ha^{-1} for soft winter wheat). Finally, the regulation of the global climate was assessed using the "carbon saturation" approach developed by Hassink (1997) to estimate the inherent maximum stock of stable organic carbon in the first 30 cm of soil. Therefore, this study assesses the soil capability for water provision and climate regulation, and the soil suitability for biomass provision and water quality regulation under a rapeseed/winter wheat crop rotation assumed as constant over the whole study area. The approximation of the actual ES supply by the soil capability or suitability to supply ES is, indeed the best compromise to incorporate a realistic representation of the soil diversity and complexity in soil-based ES assessment (Choquet et al., 2021).

A minor change was however introduced in the assessment of the regulation of water quality with reference to the approach of Choquet et al. (2021), who did not model any catch crops in order to be as close as possible to real field conditions and to enable the comparison of modelled and measured levels of services. Here, we introduced intermediate crops in order to decrease N availability during the winter. This leads to a decrease in the imbalance between N inputs and N uptake by plants and to increase the relative weight of soil processes and properties. To assess the impact of changing the scale of input soil data on the spatial co-occurrence (Obiang Ndong et al., 2020) of the four considered services, each individual indicator of ES was rescaled between 0 and 1 using the lowest and the highest scores of the M-SQR, SENSIB and MERLIN empirical models or the lowest and the highest levels of carbon saturation observed in France (Angers et al., 2011). The scores of the four considered services were eventually averaged to obtain the joint supply of soil-based ESs, following Choquet et al. (2021).

In the final step, the spatial distributions of soils represented in each of the S1000, S250 and S50 maps were used as a basis for the mapping of the levels of individual soil-based services as well as of their spatial co-occurrence at the scales 1:1,000,000 (S1000), 1:250,000 (S250), and 1:50,000 (S50), respectively.

2.4 | Quantifying and mapping the effects of changing the scales of soil input data on the levels and spatial distributions of soil-based ESs

The effect of changing the scale of soil input data on the levels and spatial distributions of soil-based ESs were quantified following two successive steps. The maps of individual services and of their spatial co-occurrence at the three scales (1:1,000,000, 1:250,000, and 1:50,000) were first compared. Then, the pedodiversity represented in the different soil maps as well as the individual and joint supply of the four considered ESs obtained in the different ES maps were computed at the landform, the land use, and the municipal levels.

2.4.1 | Comparing the soil-based ESs maps at 1:1,000,000, 1:250,000, and at 1:50,000

In order to compare the maps of individual soil-based services and of their spatial co-occurrence, deviation maps showing the relative difference in ESs level were calculated according to Huang (2017) and Zhang (2018).

First, the geometric intersection of the two soil polygons from the S1000 map, of the 23 soil polygons from the S250 map and of the 170 soil polygons from the S50 map was calculated using ArcGis (Figure 1g). This intersection resulted in 535 single-part polygons, each of them characterised by a particular combination of soil SMUs according to their initial classification in the S1000, S250 and S50 maps. Among these 535 single-part polygons, "slivers" were detected using two size-based thresholds, as suggested by Delafontaine et al. (2009). A systematic threshold allowed to assume as "slivers" all the polygons with an area lower than $0.0025 km^2$. Finally, a controlled threshold was used to detect all the polygons with an area ranging from 0.0025 to 0.005 km^2, which were individually checked and classified as "sliver" polygons if they showed the typical elongated "sliver" shape or if they did not represent a real entity. The 115 polygons classified as "sliver" polygons, with a total area of 0.093 km^2, were finally removed.

For each of the 420 remaining polygons, relative deviations were computed according to the following equation:

$$ES_{variation} = 100 \times \left(\frac{ES_{coarse} - ES_{fine}}{ES_{fine}} \right) \quad (1)$$

where $ES_{variation}$ is the relative variation in ESs level between two soil maps at different spatial scales and ES_{coarse} and ES_{fine} are the levels of services associated, respectively, with the soil maps at coarser and finer scales. The final difference is represented as a percentage, with negative or positive values depending on whether the finer soil map displays a final ESs level, respectively, higher or lower than the coarser soil map. Zero values indicate that no change in ESs level occurs when switching scales.

2.4.2 | Quantifying pedodiversity and aggregating soil-based ESs at the landform, the land use and the municipal levels

The pedodiversity, the individual ESs levels and the spatial co-occurrence of the four considered services from the different soil and ESs maps were aggregated at the landform, the land-use, and the municipal levels. Landform (Figure 1a), categorised here as plateau (SMUs 100–180), slope (SMUs 200–230) and valley (SMU 300), is indeed one major factor of soil spatial variation and it is frequently thought to drive scale effects on ESs levels (Bagstad et al., 2018; Grêt-Regamey et al., 2014). Land uses (Figure 1b), categorised here as cultivated and natural lands, are, on the other hand, one of the most common basic units for ESs mapping, particularly when matrix or look-up table approaches are used (Burkhard et al., 2009; Jacobs et al., 2015; Roche & Campagne, 2019). Municipalities, finally, are the lowest administrative level in charge of spatial planning in France.

The Shannon's entropy (H) is a common method to assess pedodiversity (Guo et al., 2003; Ibánez et al., 1995; McBratney & Minasny, 2007). It was computed for each of these spatial units according to the equation

$$H_k^s = -\sum\nolimits_{i=1}^{n} p_{k,i}^s \ln p_{k,i}^s \quad (2)$$

where s refers to the scale of the map used as primary data for calculations, that is, S1000, S250, or S50; k refers to the aggregation unit, that is, plateau, slope or valley for the landform, agricultural or natural for the land-use and one of the 14 municipalities of the Saclay plateau; p_i is the relative area of soil type i in the considered aggregation unit and n is the number of soil types in the same unit.

The individual ESs levels and their spatial co-occurrence at the landform, the land-use and the municipality levels were computed using the following equation:

$$ES_k^s = \sum_{i=1}^{n} \frac{ES_{k,i}^s \times A_{k,i}^s}{A_{k,i}^s} \quad (3)$$

where s and k have a similar meaning than in Equation 2; ES_i is the ESs level in each specific polygon i included in the landform, land-use or municipality k at the scale l; A_i is the area of the polygon i and n is the number of polygons included in the landform, the land-use or the municipality k at the scale l.

3 | RESULTS

3.1 | ESs levels at the 1:50,000 scale

On plateau positions (SMUs 100–180), the production of biomass regularly decreases from high levels in the centre (SMU 100, Figure 2) to low levels at the edges of the plateau as the thickness of the soil layers developed in silty loamy material decreases (SMUs 110–160, Figure 2) and finally vanishes (SMU 170, Figure 2). The progressive exposure of the underlying clayey materials at the soil surface indeed limits the rooting depth, increases the intensity of waterlogging and is accompanied by increasing coarse fragments contents (Table S1), which reflect soil properties limiting biomass supply. Conversely, biomass is relatively high in thalwegs where redistributed silt loam soil particles accumulate. On sloping positions (SMUs 200 to 230), the provision of biomass shows intermediate values (between 0.4 and 0.6, Figure 2) as a result of the negative impact of the slope and of the appearance of sandy materials (Table S1). More specifically, the provision of biomass increases from the steep upper slope positions (SMU 200), very rich in coarse fragments, to gently sloping lower positions (SMUs 220 and 230) slightly enriched in silty soil particles (Tables S1 and S2). Finally, valley soils also show a limited potential for biomass provision as a result of a strong hydromorphy from the soil surface (Table S1).

Water provision is at its highest in the SMUs 200, 210 and 300 (Figure 2). The high level of water provision in the SMU 300 is related to the shallow alluvial groundwater. The presence of high coarse fragment contents and sandy textures allows a very good water infiltration in SMUs 220 and 210 whereas the increasing content of silty soil particles enhances water retention and limits deep infiltrations in SMUs 220 and 230 (Table S2). The service level is moderate in plateau soils due to their silty textures and it

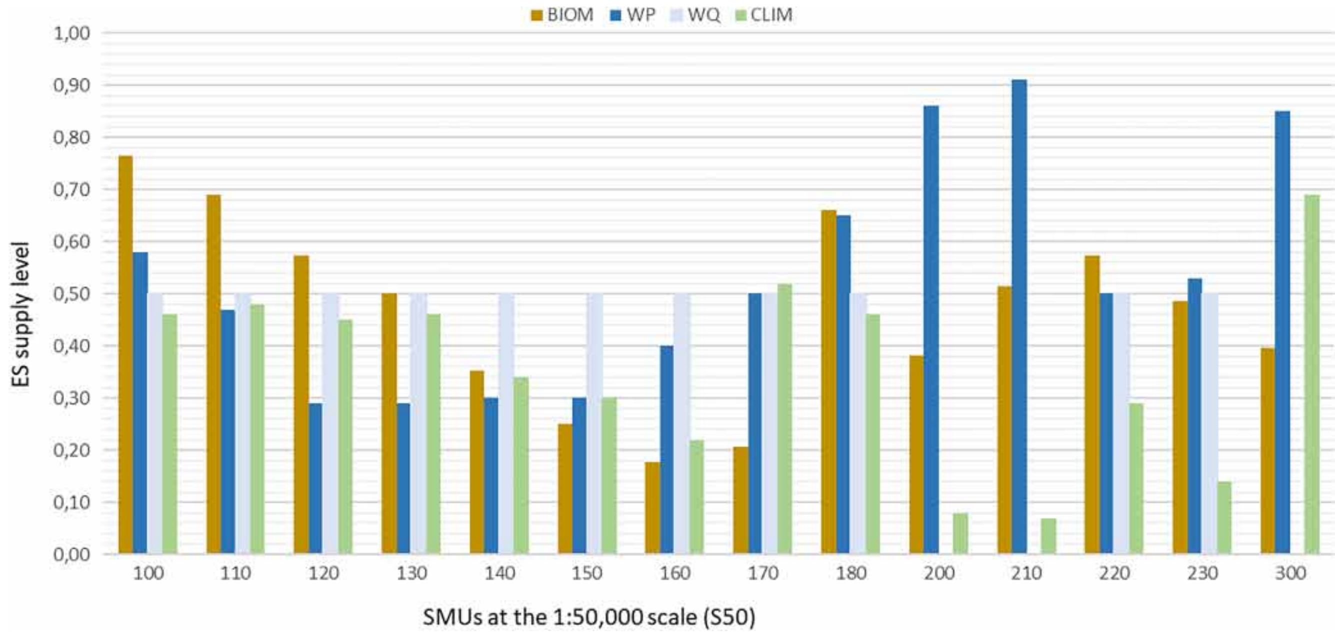


FIGURE 2 Levels for the four selected Ecosystem Services (ES): biomass provision (BIOM), water provision (WP), water quality regulation (WQ), and climate regulation(CLIM) in each of the 14 Soil Map Unit (SMU) of the soil map at the 1:50,000 scale.

regularly decreases from the centre (SMU 100) to the border of the plateau (SMU 150) with the appearance of the clayey materials acting as a hydraulic barrier impeding deep infiltration. When clayey materials are close to the soil surface (SMU 160) or at the soil surface (SMU 170), the service is supposed to increase as a result of a lowered sensitivity to soil crusting. Such increasing water provisioning is, however, doubtful in soils involving heavy clay soil layers prone to impede deep infiltration.

Globally speaking, no soil of the Saclay plateau fully prevents nitrogen leaching nor assures a full service of water quality regulation (Figure 2). The regulation of water quality is minimum in the SMUs 200, 210 and 300 characterised by low levels of biomass provision (i.e., by low amounts of nitrogen immobilised in plant biomass) and by high levels of water provision (i.e., high quantities of water that infiltrate through soils). For all the others soils showing either a high level of biomass provision or a low level of water provision, the level of service of water quality regulation is intermediate (Figure 2).

Finally, the regulation of climate is high in clayey surface soils of the SMU 300, intermediate in silty surface soils of the SMUs 100, 110, 120, 130 and 180 or in the clayey stony surface soil of the SMU 170, and low in stony and/or sandy surface soils of the SMUs 140, 150, 200, 210, 220 and 230 (Figure 2).

As already observed by Choquet et al. (2021) for the five SMUs from the S250 map, the variability of the levels of individual services among the various SMUs from the S50 map are coherent with the variability of the soil properties except for water provision in the SMU 160 and 170 where the service level appears overestimated. Moreover, the levels of the various individual services are consistent with each other as shown by the low levels of water quality regulation in case of both low levels of biomass provision and high levels of water provision. As a result, these data may be used to map the spatial distribution of the four considered soil-based services with a reasonable level of confidence.

3.2 | Scale effect on the level and spatial distribution of ES

When the service levels are averaged over the entire Saclay Plateau, a change in the scale of input soil data has almost no impact on the assessment of water provision (Figure 3b), slight impact (around 10%) on the assessment of water quality regulation (Figure 3c), and only moderate impact (around 20%) on the assessment of biomass provision and climate regulation (Figure 3a,d). With averaged scale effects around 10%, the assessment of the joint supply of the four considered services is only slightly affected by changes in the scale of input soil data (Figure 4). Whatever the ES, most of these scale effects are observed between the ES1000 and ES250 maps (Figures 3 and 4). The ES250 and ES50 maps are contrastingly very close (Figures 3 and 4).

However, the averaged ESs levels over the Saclay plateau hide a much more complex situation. Compensation effects are indeed observed for the four studied

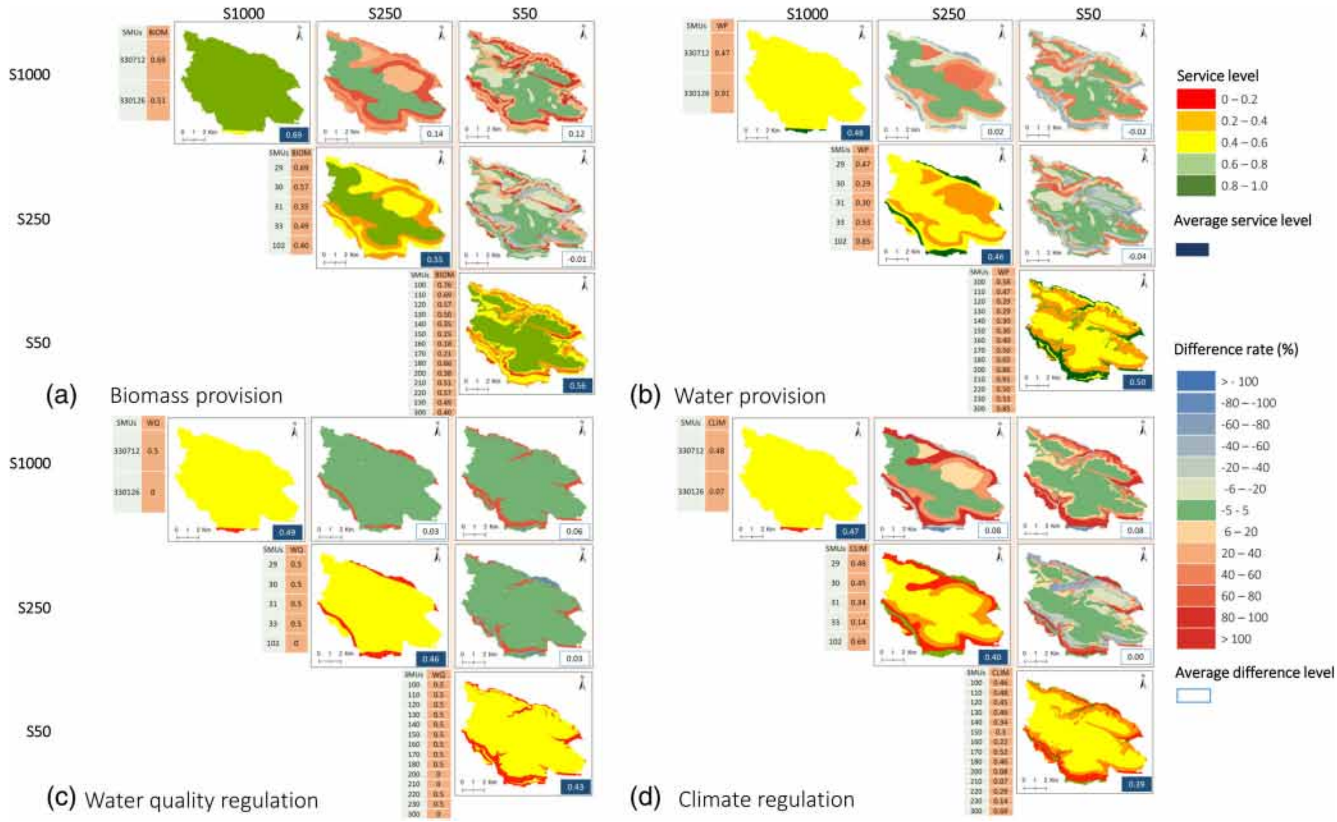


FIGURE 3 Maps for the four selected Ecosystem Services (ESs) according to the different soil maps used as input data for the assessment (i.e., S1000, S250, S50). Maps at the intersection between similar scales in lines and in columns are the ES maps derived from the soil map at this particular scale. Maps at the intersection between different scales in lines and in columns represent the relative difference between ES maps derived from the soil map at the scale in line minus that at the scale in column. The numbers at the bottom right of these maps indicate the averaged ES level or the averaged difference between ES levels over the whole study area respectively in ES maps and in ES deviation maps. The tables detail the ES levels in Each Soil Mapping Unit (SMU) at each spatial scale for the considered ES: biomass production (BIOM), water provisioning (WP), water quality regulation (WQ) and climate regulation (CLIM).

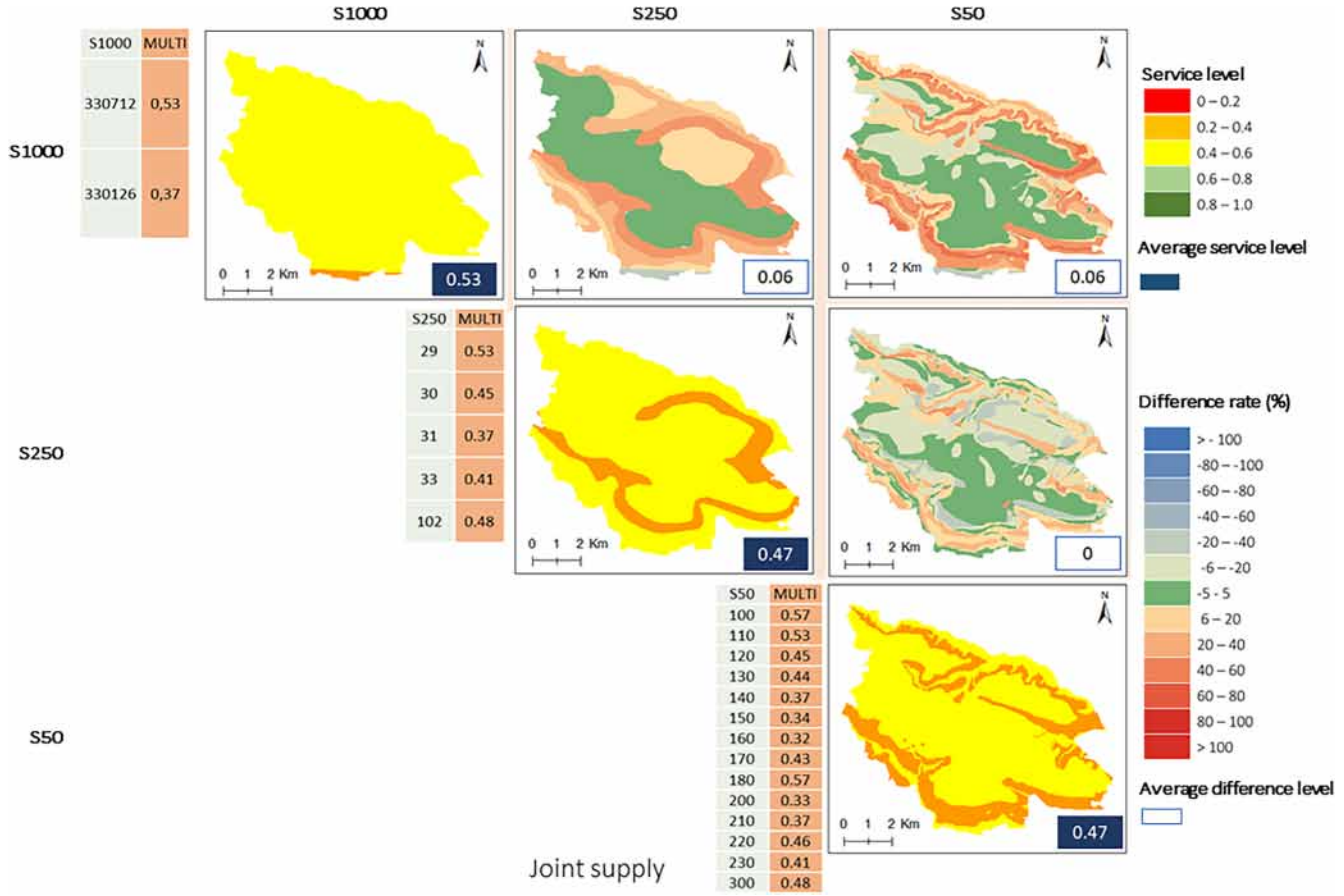
services as well as for their joint supply. Scale effects may be locally positive (i.e., resulting in an overestimation of the service levels at coarser scales) or negative (i.e., leading to an underestimation of the service levels with coarser scales). Some scale effects are in addition of a large magnitude, easily exceeding 75% and even reaching 100% in some occasions, but highly localised as illustrated by the regulation of water quality (Figure 3c). Other scale effects are contrastingly of low magnitude (i.e., between 20% and 50%) but concern large parts of the studied area. This is typically observed for water provision (Figure 3b) or the joint supply of services (Figure 4). The most sensitive services to different scales, that is, the provision of biomass and the regulation of climate, simultaneously show these two kinds of scale effects (Figure 3a,d).

The scale effects of the highest magnitude are generally observed on plateau edges (SMU 31 in S250 or SMUs 140, 150 and 160 in S50, Figures 1, 3 and 4) with the exception of water provision for which they are mostly localised on sloping areas (SMU 33 in S250 and SMUs 200, 210 and 220 in S50, Figures 1, 3 and 4). Whereas the shift from S1000 to S250 maps clearly highlights the specific functionality of soils from plateau edges and slopes, the shift from S250 to S50 also shows similarly large but localised differences (Figures 3 and 4). It indicates that the supply of the soil-based services is non-clustered but shows a high spatial variability, even over very short distances.

3.3 | Scale effect on ESs delivery at different levels of spatial aggregation

3.3.1 | Scale effects according to landforms

The S1000 and ES1000 maps show respectively a low pedodiversity, particularly for plateau positions (Figure 5a), and similar ESs levels among the different types of landform (Figure 5b–f). Switching to finer scales does not only result,



S1000	MULTI
330712	0,53
330126	0,37

S250	MULTI
29	0.53
30	0.45
31	0.37
33	0.41
102	0.48

S50	MULTI
100	0.57
110	0.53
120	0.45
130	0.44
140	0.37
150	0.34
160	0.32
170	0.43
180	0.57
200	0.33
210	0.37
220	0.46
230	0.41
300	0.48

FIGURE 4 Maps of the spatial co-occurrence of the four selected Ecosystem Services (ESs) or joint-supply of the four selected ESs according to the different soil maps used as input data for the assessment (i.e. S1000, S250, S50). Maps at the intersection between similar scales in line and in column are the ES joint-supply maps derived from the soil map at this particular scale. Maps at the intersection between different scales in lines and in columns represent the relative difference between ES joint-supply maps derived from the soil map at the scale in line minus that at the scale in column. The numbers at the bottom right of these maps indicate the averaged ES joint-supply or the averaged difference between ES joint-supplies over the whole study area respectively in ES joint-supply map and in ES joint-supply deviation maps. The tables detail the ES joint-supply for each Soil Mapping Unit (SMU) at each spatial scale.

as expected, in increasing pedodiversity levels, either globally (Figure 1) or whatever the scale or the landform considered – except for the valley areas at the scale 1:50,000 (Figure 5a) – but also in increasing discrepancies of ESs levels between landforms (Figures 5b–e). In the ES250 and ES50 maps, biomass provision and water quality regulation services are indeed lower by 20 to 100% in sloping and valley areas than in plateau depending on the map scale, the service or the landform type considered (Figures 5b–e). Water provisioning levels are contrastingly higher in these two finer maps in sloping and valley positions than in plateau (Figures 5b–e). Climate regulation shows a very particular pattern with the lowest levels observed in slope areas and the highest in valley positions. Finally, unlike when analysing individual services, the scale effect does not affect the joint supply of ESs when aggregated at the landform level except for a slight decrease in sloping areas (Figure 5f).

3.3.2 | Scale effects according to land-use

When aggregated at the land use level, the S1000 map shows negligible to very low levels of pedodiversity (Figure 5a) and the ES1000 map shows very similar ESs levels in the cultivated and forested areas (Figure 5b–e), which is not the case at finer scales. The pedodiversity levels indeed increase at those finer scales: (i) with a similar magnitude in cultivated and natural lands in the S250, and (ii) with a higher magnitude in natural lands in the S50 maps where pedodiversity is particularly high. At fine scales, the levels of all the considered services, except for water provision, and their joint supply, are higher in cultivated areas than in natural ones (Figure 5a–f).

In cultivated lands, despite the sizeable increases of pedodiversity levels observed, switching spatial scales

FIGURE 5 Soil diversity (a) and soil service individual- and joint-supply levels (b–f) according to the three soil maps used as input data for the assessment (i.e. S1000, S250 and S50) and the different spatial levels of aggregation (i.e., relief, land use, and municipality).

has almost no impact on ESs levels (Figure 5a–e). Contrastingly, ESs levels change with scales in the natural lands. Scale effects around 20% are indeed observed for water provision as well as for the joint supply of ESs (Figure 5d,f). These effects reach around 50%, 70% and even 80% for the regulation of water quality, the production of biomass and the climate regulation, respectively (Figure 5b,e). Most of these changes result from the shift from the ES1000 to the ES250 maps (Figure 5b–f). Natural lands indeed show similar levels of all the considered services in the ES250 and the ES50 maps (Figure 5b–f), despite the higher pedodiversity in the S50 map (Figure 5a).

3.3.3 | Scale effect according to municipality division

The S1000 map shows an almost null pedodiversity in all municipalities but two (i.e., Bures-sur-Yvette and Gif-sur-Yvette), that are partly in the Yvette valley where Arenosols are mapped (Figure 1). The pedodiversity described in soil maps progressively increased when switching to finer scales (Figure 5a). In the S50 map, six municipalities show pedodiversity levels higher than 2: Buc, Orsay, Villiers-le-Bâcle, Châteaufort, Vauhallan, Les-Loges-en-Josas and finally Jouy-en-Josas (Figure 5a).

The ES1000 maps show very similar levels between municipalities for all the considered services and consequently for their joint supply. Higher discrepancies between municipalities are found when aggregating services at municipality level from input soil data at finer scales. Scale effects are of low intensity for most municipalities. They may however reach 20% for water provision (in Bures-sur-Yvette, Figure 5c), 80% for biomass provision (in Igny, Figure 5b), and even 130% for climate regulation (in Igny, Figure 5e), or 150% for the regulation of water quality (in Bures-sur-Yvettes, Figure 5d). Moreover, albeit switching scales generally resulted in decreasing levels of biomass provision and water quality or climate regulation, this is the reverse for water provision (Figure 5b–e). Finally, most of these scale effects are linked – in intensity or in direction – to the shift from S1000 to S250 maps. However, such rule is not systematic. In Igny, the shift from S250 to S50 maps indeed induces a decrease in the levels of provisioning and regulating water services of similar or higher intensity than the shift from S1000 to S250 maps. In Bures-sur-Yvette, the shift from the S250 to the S50 maps induces a decrease of climate regulation service, unlike the shift from S1000 to S250 that induces an increase instead.

4 | DISCUSSION

4.1 | Scale effects on levels and spatial distribution of soil-based services

When averaged over the whole study area, the ESs level estimated with the S1000 map does not differ by more than 20% from the ESs levels derived from the S250 and S50 maps (Figure 3), regardless of their different degrees of spatial detail. Such scale effects have a similar magnitude as those quantified when one increases the spatial details of land-use data (Bagstad et al., 2018; Grêt-Regamey et al., 2014), digital elevation model (Hamel et al., 2017) and carbon stocks or storage (Zhang, 2018). At first sight, these effects may be considered as almost insignificant, suggesting that the three soil maps might be equally useful tools whenever only an averaged ESs level over the study area is needed.

However, the four considered services are not equally sensitive to scale effects. For instance, the effect is particularly strong for biomass provision as also observed by Grêt-Regamey et al. (2014), and conversely less strong for water provision or water quality regulation (Bagstad et al., 2018; Grêt-Regamey et al., 2014). It is clear, however, that the sensitivity of ESs to scale effects is context specific (Hamel et al., 2017; Rioux et al., 2019; Zhao & Sander, 2018). For example, the relative deviation of carbon stocks or carbon storage with scale is generally under 10% (Bagstad et al., 2018; Grêt-Regamey et al., 2014; Zhang, 2018), making of climate regulation – usually assessed using carbon stock indicators – one of the services that is least sensitive to scale effects. Conversely, this service is one of the most sensitive services to scale effect in the present work.

Finally, whereas the relative deviations of ESs levels averaged over the whole study area are low and mainly related to the change from the S1000 to the S250 maps, significant discrepancies among local ESs levels exist and persist when changing from the ES250 to the ES50 maps (Figure 3). These local deviations range from a few 10s to several 100% (Figure 3), as commonly observed (Bagstad et al., 2018; Zhang, 2018). These differences clearly highlight that whereas the scale effect has only a slight impact on averaged ESs levels, it has a very strong impact on their spatial distribution (Bagstad et al., 2018; Grêt-Regamey et al., 2014; Zhang, 2018). Soil diversity indeed decreases with coarser scales, since an almost completely homogenous soilscape is considered in the S1000 map (Figure 1). Coarse scales thus induce generalisation errors (Baveye et al., 2018; Eigenbrod et al., 2010; Kangas et al., 2018) due to the homogenisation of ESs levels, which is even more important as the missing soil units were characterised by particularly high or low levels of ES.

4.2 | Use of land-use/land-cover matrix approaches to map soil-based ecosystem services

Due to the poor availability of soil data and to the widespread availability of land-use/land-cover (LULC) data, LULC classes are by far the most widely used type of basic units to map ESs supply (Andrew et al., 2015; Martínez-Harms & Balvanera, 2012; Shen et al., 2021). Such approaches ignore the impact of soil diversity inside LULC patches on ESs levels among other spatially varying factors, which is one of their well-known limitations (Baveye et al., 2018; Jacobs et al., 2015). Ignoring soil diversity may be acceptable for agricultural lands in which aggregated ESs levels are almost unaffected by the progressive introduction of soil diversity with finer-scaled soil input data (Figure 5b–e). It is however clearly not the case for natural lands in which aggregated ESs levels are strongly sensitive to a more detailed description of the soil diversity (Figure 5b–e). Indeed, natural lands are mostly located on slope and valley parts of the study area, where maps at fine scales are required to represent soils covering small areas, but with specific ESs signatures.

In the so-called "matrix" approaches, the levels of ESs assigned to each LULC class are often based on expert judgement (Burkhard et al., 2012; Jacobs et al., 2015; Roche & Campagne, 2019). In such cases, natural or forested lands are generally considered as hotspots for ESs delivery following the general rule "the more anthropised the area, the lower the ESs supply level" (Sohel et al., 2015). More specifically, whereas agricultural lands provide high levels of provisioning services – especially biomass production – natural and forested lands are often considered as high providers of regulating services, in particular global climate regulation, groundwater recharge (i.e., water provision), or water purification (Burkhard et al., 2012; Guan et al., 2020; Helfenstein & Kienast, 2014; Roche & Campagne, 2019). However, such binary pattern does not seem systematic. For instance, agricultural lands, rather than natural and forested lands, achieve the highest joint-supply in the study area, at least in the ES250 and ES50 maps (Figure 5f). Furthermore, regulating ESs levels aggregated over cultivated lands may be relatively similar (regulation of water quality) or even higher (regulation of climate) than those aggregated over natural lands. Indeed, in the studied case as well as in others (e.g., Vazquez et al., 2020), cultivated soils are not only those with the highest potential of biomass provision but more generally achieve the highest degree of multifunctionality.

4.3 | Soil typology and soil functionality

The recognition of scale effects on the levels of the considered ESs suggests that there is a relationship between soil diversity and soil functionality. To characterise this relationship, absolute changes from the ES1000 to the ES50 maps in the ESs levels aggregated according to landforms, land uses or municipalities are plotted against similar absolute changes in pedodiversity (Figure 6a–d). As suggested in other studies (Scammacca et al., 2022), Figure 6 clearly shows quantitatively that changes in pedodiversity do not induce direct, simple or systematic changes in ESs levels. Several interesting behaviours may however be recognised.

First, even low changes in pedodiversity can lead to changes in ESs levels largely above the mean observed changes (Figure 6a–d). This is notably the cases for valley (with the exception of climate regulation) and sloping (with the exception of biomass provision) areas and some municipalities like Igny, Bures-sur Yvette, or Gif-sur-Yvette either for most services (Igny) or for water services (Bures-sur Yvette and Gif-sur-Yvette). These municipalities are largely localised on sloping areas, characterised by only four different SMUs, among which SMU 220 predominates, and which implies relatively low soil diversity (Figure 5a). Among these four SMUs, SMUs 200 and 210 show very specific properties, including sandy textures (Table S2), leading to particularly high levels of water provision and low levels of water quality regulation (Figure 3). In such cases, the large changes in ESs levels with finer soil map scales are not related to the introduction of soil diversity but to the introduction of soils showing highly contrasted properties and consequently highly contrasted functionalities.

Contrastingly, high changes in pedodiversity may have relatively low and even no impact on ESs levels aggregated at the landform, the land-use, or the municipal levels. This is notably the case for agricultural lands, for plateau landform and for municipalities like Guyancourt, Buc, Villiers-le-Bacle, or Jouy-en-Josas (Figure 6a–d), these municipalities being, at least partly, occupied by agricultural soils on plateau positions (Figure 1). Although relatively high (Figure 5a), the diversity of agricultural soils is notably constituted by four variants of Luvisols (SMUs 100–130) showing very similar surface properties and differing mainly through their subsoil horizons (Table S2). Because of their similar properties, all of these soils show similar ESs delivery (Figure 2). The differentiation of such soils in ESs assessment and mapping is then useless.

Finally, when the description of pedodiversity is progressively detailed from the S1000 to the S250 and S50

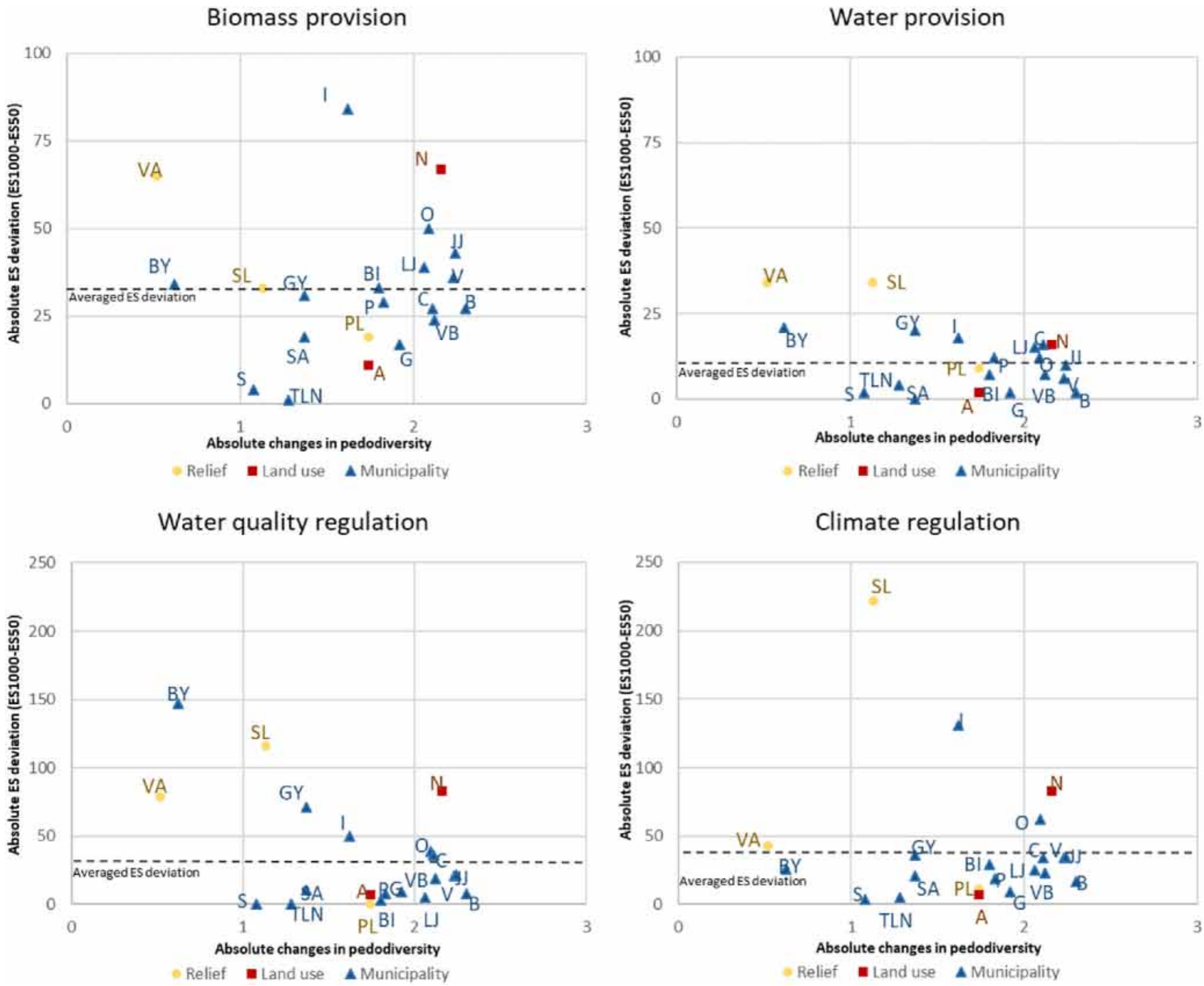


FIGURE 6 Relationship between absolute changes in pedodiversity and in ES supply (ES1000-ES50) according to the aggregation at the relief (with PL = plateau; SL = slope; VA = valley), land-use (with A = agricultural; N = natural) and municipal levels (with TLN = Toussus-Le-Noble; S=Saclay; SA = Saint Aubin; P=Palaiseau; G = Guyancourt; B=Buc; BI=Bièvre; O=Orsay; VB = Villiers-le-Bacle; C=Chateaufort; V=Vauhallan; I=Igny; LJ = Les-Loges-en-Josas; JJ = Jouy-en-Josas; BY = Bures-sur-Yvette; GY = Gif-sur-Yvette.

maps, most of the changes in ESs levels are observed between the ES1000 and the ES250 maps. The relatively coarse description of the soil diversity in the S250 map seems then sufficient to consider the main part of the soil functional variation (Figure 5a–e). Nevertheless, this is not the case for water provision and regulation and for climate regulation in sloping areas, in natural areas and in municipalities like Igny, Gif-sur-Yvette or Bures-sur-Yvette (Figure 5b–e). As, discussed above, such changes are mainly explained by the skeletic Regosol (SMU 200) and the Arenosol (SMU 210), that have an area too low to be recognised and mapped at the scale 1: 250,000, but have, because of their properties, very specific service signatures: high levels of water provision and low levels of water and climate regulation (Figure 2).

4.4 | Operational implications

We used here three conventional soil maps at different spatial scales to assess and map four soil-based services on the Saclay plateau, a territory with an area of 100 km^2. On this specific area, the three soil maps turn out to be equally useful tools when averaged ES levels are required on the overall area considered. When the extent of the area of interest decreases from 100 to 10 km^2 or less, which is the typical area of the French municipalities in the area, only the two finest soil maps (S250 and S50) provide similar aggregated ESs levels. As soon as a non-spatialised ES assessment is needed on the whole area – for instance in order to assess and compare the supply and demand of ESs, or to monetise different services (Huq et al., 2019) – one could argue that a pragmatic rule of thumb would recommend the use of the coarsest map scale as the best option as it significantly reduces the complexity of the assessment without inducing a significant change in ESs levels. Such "best options" are then the S1000 for areas over 100 km^2 and the S250 map for areas over 10 km^2.

The three soil maps contrastingly provide very different ESs spatial patterns, which is of considerable interest when it comes to identify the location of specific soil-based ESs, as for instance in order to identify ESs hotspots and protect them through the implementation of adequate planning and management strategies (Sannigrahi et al., 2019). In such cases, using the S1000 map or, to a lower extent the S250 map, as input soil data to map the ESs spatial distribution might lead to misinformed environmental policy decisions (Nussbaum et al., 2011), at least when used on the studied territory of spatial extent lower than 100 km^2.

Our results show that it is not straightforward to identify the optimal representation of pedodiversity required to fully describe the spatial variability of ESs levels. Such optimal level can be seen as the degree of details under which ESs levels and spatial patterns are sensitive to coarser representation of the pedodiversity and above which ESs levels and patterns are almost unsensitive to finer representations of the pedodiversity. The need to integrate soil data in ESs assessment and mapping is indeed related to the contrasts between the physical, chemical and biological properties of the different soil units rather than to the density or numbers of typological units identified and represented (Mikhailova et al., 2021). This study shows that shifts to finer scales from one Reference Soil Groups to another (RSGs, IUSS Working Group WRB, 2015) generally influence the ESs levels and spatial patterns. These are, for example, the cases with the shift from the Luvisol in the S1000 map (SMU 330712) to the Planosol (SMU 31) and the Cambisol (SMU 33) in the S250 map or with the shift from the Cambisol (SMU 33) in the S250 map to the Regosol (SMU 210) and the Arenosol (SMU 220) in the S50 maps (Figure 3). Such functional impacts are considerably lower when the shift to finer scales occurs between different variants of the same RSGs as from the Luvisol in the S1000 map to the katostagnic Luvisol in the S250 map (SMU 30) or to the haplic Luvisol (SMU 100), katostagnic Luvisol (SMU 120) or pantostagnic Luvisol (SMU 130) in the S50 map (Figure 2). This observation suggests that an optimal representation of soil diversity could involve the identification in a given region of all the RSGs. Such RSGs are indeed intended to take into account the key differences in soil horizons, properties and materials whereas finer classification levels are intended to describe variations within RSGs through the use of qualifiers (IUSS Working Group WRB, 2015). Unfortunately, it is unlikely that the optimal representation of soil diversity, that is, the identification of all the RSGs in a given area, matches with one of the common scales for soil mapping. In the studied site, although most of the RSGs are identified at the scale 1:250,000, some of them may only be identified at finer scale due to their low areas, as for instance the Regosol (SMU 200) and the Arenosol (SMU 210) in the S50 map.

The need to take into account the spatial variability of soil functionality in ESs assessment appears more specifically relevant in the forested and natural areas. Indeed, cultivation likely involves the biased selection of deep, homogeneous and freely-drained multifunctional soils and/or avoids particular geological or topographical conditions giving rise to marginal soils with very specific ESs signatures. In our study site, this is for example the case with the different Planosols partly developed on shallow clayey deposits, of the Regosols and the Arenosols developed in sandy materials and on steep slopes, or with the Gleysols developed in valley bottoms. As a result, the intermediate (S250) or even coarse (S1000) description of the soil variability may be sufficient as soon as ESs assessments are limited to agricultural soils whereas finer ones (S50) seem mandatory for the assessment of soil-based services in forested and natural areas.

The comparison of the ESs levels and patterns obtained from the three considered conventional maps proved to be helpful to define guidelines for managing the balance between the availability and the scale of input soil data among which (i) the possibility to use coarser scale soil data in agricultural areas than in forested or natural areas or (ii) the usefulness of the input soil data at the 1:250,000 and 1:50,000 scales to assess ESs levels when aggregated on areas respectively >100 and 10 km^2. However, it is likely that such guidelines derived from a particular case study are context-dependent and still need to be verified in other pedological contexts. Nevertheless, to our knowledge, this is the first assessment on the finest ES mapping grains that are achievable for ES mapping based on conventional soil maps. By providing spatially exhaustive soil data at fine resolution, the development of digital soil maps should be very helpful to resolve the trade-off between the availability and the degree of spatial details in input soil data. However, while it is possible to judge the consistency between the ESs levels and patterns obtained from conventional or digital soil maps at various scales or resolution, it will remain impossible to know how far these maps are from the truth as long as field measurements of ESs levels are lacking (Baveye, 2017; Chalhoub et al., 2020).

5 | CONCLUSION

ES assessment and mapping are useful tools to support policy making related to land-planning strategies or land management at different spatial levels. Most ESs mapping exercises are based on LULC data and consequently ignore soils and their diversity inside LULC patches. Comparing the levels and patterns of four soil-based ESs obtained from three conventional soil maps, we showed here, however, that changing the level of detail in the description of soil diversity completely changed the picture. The crucial point in this respect is the adequacy between the spatial scale of the input soil data with the objectives and spatial extent of the soil-based ESs assessment.

In the study area, the soil maps at the 1: 1,000,000 and 1:250,000 scales are found sufficiently detailed to obtain levels of services close to those obtained with the finest scale when aggregated over areas of 100 to 10 km^2, respectively. However, such coarse map scales only provide a poor description of the ESs spatial distribution with reference to that derived from the soil map at the 1:50,000 scale. Identifying a priori the optimal description of soil diversity to obtain a reliable representation of the ESs spatial diversity is a complex task as the sensitivity of services to scale effects is context-specific and highly variable among individual ES. In any case, it is clear that pedofunctionality cannot be simply inferred from the soil typological diversity represented in soil maps. Differences in soil functionality are indeed related to the contrasts existing between the soil properties of the different soil units rather than to the density or numbers of typological units. If the Reference Soil Groups of the World Base for Soil Resources, or similar concepts in other soil classifications, appear as an interesting way to take into account most of the spatial heterogeneity in pedofunctionality, the translation of traditional typological soil classifications into functional classifications could be of particular interest for the integration of soils in ESs assessment and mapping.

AUTHOR CONTRIBUTIONS

Ottone Scammacca: Conceptualization; investigation; writing – original draft; methodology; formal analysis. **Ophélie Sauzet:** Conceptualization; investigation; writing – review and editing. **Joel Michelin:** Conceptualization; investigation; writing – review and editing; formal analysis. **Pauline Choquet:** Conceptualization; investigation; writing – review and editing. **Patricia Garnier:** Conceptualization; investigation; writing – review and editing. **Benoit Gabrielle:** Conceptualization; investigation; writing – review and editing. **Philippe C. Baveye:** Conceptualization; investigation; writing – review and editing. **David Montagne:** Conceptualization; investigation; funding acquisition; writing – original draft; methodology; writing – review and editing; formal analysis; project administration; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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