

Original articles

Spatial hotspots and bundles of soil functions across Europe

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ABSTRACT

A challenge in soil research is determining how multifunctional soils respond to a change in management and the environment. This is because soil functions are not independent of each other: complex interactions occur between functions across spatial scales. While a growing body of literature has attempted to quantify soil functions, few studies identified sites of multiple functions occurrence for large geographical areas. In this study, we investigate the spatial overlap between multiple soil functions in European croplands and grasslands. We generated maps of five soil functions using existing multi-attribute models developed for the large-scale assessment of soil functions. Out of these maps, we identified spatial hotspots, i.e. locations that concomitantly have a high supply of several soil functions and spatial coldspots, i.e. areas providing a low supply of functions. A cluster analysis combined with a hierarchical agglomerative clustering further revealed spatial bundles of functions, i.e. a set of soil functions that repeatedly appear together in space. Our analysis shows that hotspots of soil functions, where all five soil functions are supply at a high level, occur only in a few geographically isolated locations in Europe, covering just 0.03% of croplands and grasslands. However, broader zones were identified where three to four soil functions were achieved at an optimal level, together accounting for about 8% of the area. Similarly, only 7% of the area had at least four functions at low supply (i.e. coldspots). The cluster analysis resulted in five bundles that provided a differentiated view on multifunctional soils in Europe, with most soils providing a low to moderate levels of all five functions. Two main bundles, covering about 60% of European croplands and grasslands, were identified: one with high biodiversity and climate regulation but low other functions, and another with high nutrient cycling and biodiversity but low remaining functions. The analysis of spatial hotspots, coldspots and bundles of functions supply may be a tool for the regional-scale management of multifunctional soil so that all regions secure a sustainable supply of soil functions. It is also a first step to avoid potential conflicts between users, by allowing collective decisions on which bundles of functions to prioritize.

1. Introduction

One of the challenges in soil science today is understanding how to balance and manage the many functions soils perform, especially as they respond to human activities and environmental pressures (Greiner et al., 2017; Rillig et al., 2019; Creamer et al., 2022). Primary productivity, habitat provisioning for biodiversity and climate regulation are just a few of the many functions supported by soils. While it is widely recognized that soils supply the multiple functions (Baveye et al., 2016), determining how this supply varies in space depending on environmental conditions, soil characteristics and management practices, is a challenge (Schulte et al., 2015). This is because soil functions are not independent of each other and complex interactions between functions appear also across spatial scales. There is, for example, a

synergy between the cycling and supply of nutrients and the primary production due to the inputs of nutrients and the resilience obtained by the input of organic matter (Schröder et al., 2016). Such interaction may occur when multiple functions simultaneously respond to the same driver. For example, it is usual to assume that artificial drainage of peats and organic soils has a positive effect on cultivation, while at the same time resulting in the decomposition of the organic matter, thus becoming a source of CO₂ and nitrous oxide (N₂O) emission (Paul et al., 2018). Because of such interaction effect between functions, actions to augment one function may detrimentally affect another.

Major frameworks that consider the assessment of soil functions, and in the broader literature ecosystem services (e.g. Bennett et al.,

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2009), require addressing interactions between functions or services as a means to produce a realistic assessment of multifunctional soils. This is usually done with the evaluation of synergies and trade-offs. This was done in Zwetsloot et al. (2021), for example, through a co-occurrence analysis between the supply of five soil functions evaluated in 94 sites across Europe. In these synergies and trade-offs approaches, a prerequisite is to obtain estimates of the soil function supply, which can be used as a basis to identify sites of multiple soil function occurrence and co-occurrence. Hereafter, we follow the definition of Lechevallier et al. (2025), who define the supply of a soil function as the amount of a function that is achieved over a given period, determined by the effective fulfilment of the underlying processes during that time.

The spatial overlap between multiple soil functions naturally leads to the identification of spatial hotspots, i.e. locations that concomitantly have a high supply of several soil functions. Individual soil functions can also be thought of as part of an interrelated whole, called a bundle (Rodríguez et al., 2006). Following Raudsepp-Hearne et al. (2010), we define hereafter a spatial soil function bundle as a set of soil functions that repeatedly appear together in space. While largely used in ecosystem services research to understand relationships among multiple services (e.g. Bennett et al., 2009), soil research has not yet tackled this concept. Bundling of soil functions supply may be a tool for the regional-scale management of soil multifunctionality. It can also serve as a tool to identify common trade-offs and synergies that occur over space and time and distinct types of multifunctionality. This, in turn, can support decision-making aimed at the further optimization of multifunctional soils.

An increasing number of studies have examined spatial bundles by mapping ecosystem services and analysing their spatial co-occurrence, that is, how these services occur together across space and time (e.g. Nelson et al., 2009). Spatial bundles are typically identified using principal component analysis (e.g. Marsboom et al., 2018) or cluster analysis of ecosystem service maps (e.g. Raudsepp-Hearne et al., 2010), employing algorithms such as *k*-means clustering or self-organizing maps (e.g. Mouchet et al., 2017). An overview of techniques to investigate spatial associations and bundles of ecosystem services is provided in Mouchet et al. (2014). An illustrative application is provided by Medina-Roldán et al. (2024), who conducted a regional case study in Italy. By clustering soil ecosystem services, they identified distinct bundles and showed that the relationships among services varied spatially, with some regions having strong synergies, while others were dominated by trade-offs.

This paper builds on Wadoux et al. (2025a), which developed models for the large-scale assessment of five soil functions across European soils (Wadoux et al., 2025b). We assessed five common soil functions: (1) primary productivity, defined as the soil's capacity to support the provision of food, fibre, and fuel; (2) habitat provision for biodiversity, reflecting the soil's role as a habitat that sustains biological communities; (3) nutrient cycling, referring to the soil's capacity to receive, recycle, and supply nutrients to plants; (4) water regulation, which represents the soil's capacity to regulate and purify water; and (5) climate regulation, representing the soil's ability to store carbon and mitigate greenhouse gas emissions. Here, we present a methodology and its application to identify hotspots and spatial bundles of soil function supply across the European continent using maps of soil functions. We contribute to the large-scale assessment of soil functions by analysing spatial associations that lead to the identification of hotspots and bundles. Maps of the five soil functions are generated using spatially explicit input attributes. The resulting maps of soil function supply are overlaid and grouped into bundles. Based on these bundles, we provide an assessment of the main groups of soil functions that co-occur in European soils.

2. Material and methods

2.1. Models of soil functions

The supply of five soil functions was quantified using the multi-attribute decision models developed by Wadoux et al. (2025a), based on the DEX (Decision Expert) method (Bohanec, 2022), implemented in the DEXi software (Bohanec, 2023). A DEX model employs a hierarchical decision tree structure, where attributes are aggregated through utility functions. The highest-level attribute is progressively decomposed into less complex attributes, each dependent on lower-level attributes. Input attributes, which may be continuous or categorical, are transformed into a discrete scale (e.g. *Low*, *Medium*, *High*, or *Presence/Absence*).

Fig. 1 shows the hierarchical structure for the model for the assessment of the provisioning of climate regulation soil function. The top-most aggregated attribute is the climate regulation soil function. The aggregated attributes rely on a set of soil, environmental (i.e. landscape and climate attributes) and management input attributes. The lower-level input attributes and aggregated attributes are aggregated through a set of utility functions given in the form of integration roles that map the values of the lower-level attributes to that of the aggregated attribute. The integration roles take the form of IF-THEN on the nominal values of the lower-level attribute and are represented in a tabular form. The utility functions were defined by expert knowledge. More information on the utility functions can be found in Wadoux et al. (2025a). The DEX model can handle missing data by assigning a set of nominal values and testing of outcomes for each value.

The models of Wadoux et al. (2025a) assess the primary productivity, habitat provision for biodiversity, nutrient cycling, climate regulation and water regulation soil functions. They were refined for use at the regional level from original base models that were published in Sandén et al. (2019), Van Leeuwen et al. (2019), Schröder et al. (2016) and Trajanov et al. (2019), Van de Broek et al. (2019) and Wall et al. (2020), while keeping the same structure and utility functions. The module attributes, i.e. the aggregated attributes directly linked to top-level attribute representing particular soil functions, are soil and environmental conditions for primary productivity; nutrients, soil structure, and hydrology for biodiversity habitat; mineralization, nutrient recovery, and nutrient availability for nutrient cycling; carbon storage, N₂O emissions, and CH₄ emissions for climate regulation (Fig. 1); and water storage, runoff, and drainage for water regulation soil function. Models were developed for cropland and grassland, with minor differences in the management input attributes. All thresholds for the discretization of continuous input variables into the qualitative discrete scales are reported in Wadoux et al. (2025a). They were derived from previous studies (i.e. Sandén et al., 2019; Van Leeuwen et al., 2019; Schröder et al., 2016; Trajanov et al., 2019; Van de Broek et al., 2019; Wall et al., 2020). When unavailable, thresholds were determined through a data-driven approach. Within each of the 11 European environmental zones (Metzger et al., 2012), thresholds were set by using zone-specific quantiles: values below the first quantile were classified as *Low*, those above the third quantile as *High*, and those between the first and third quantiles as *Medium*.

2.2. Soil, environmental, climate and management input attributes

The multi-attribute models use predefined soil, environmental, and site variables as inputs. We collected a set of 34 spatially exhaustive soil, environment, climate and management variables required as input attributes. All input attributes were reprojected to the Lambert Azimuthal Equal Area (EPSG:9820) projection system and cropped to conform with the same extent. The extent comprises the countries of the European Union and adjacent countries (e.g. Iceland, United Kingdom, Norway) which had available input attributes. All input attributes were either resampled using bilinear interpolation or aggregated to conform

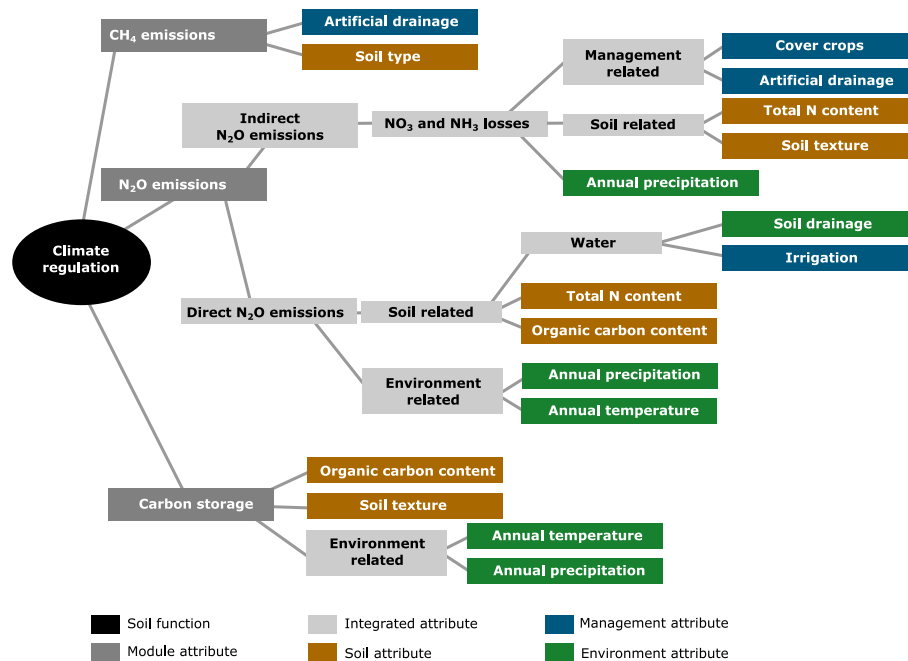


Fig. 1. Structure of the model for the climate regulation soil function. Grey rectangles represent aggregated attributes and coloured rectangles are soil, management or environmental input attributes.

with a spatial resolution with grid cells of $1000 \text{ m} \times 1000 \text{ m}$. The complete list of variables along with their unit, reference and the functions in which they are used is presented in Table 1.

The datasets used in this study represent the best available, spatially exhaustive sources covering soil, environmental, climate, and management attributes at the European scale (Table 1). These data products were compiled from multiple sources collected between approximately 2005 and 2024. Most describe long-term mean or baseline conditions rather than single-year measurements, and are designed for use in European-scale environmental modelling. Accordingly, these datasets capture stable patterns of soil and environmental conditions rather than short-term temporal variability.

2.3. Mapping

Mapping of soil functions was performed by applying the multi-attribute soil function models to input data obtained for a fine grid covering the entire surface of Europe. At each cell center, the model was run for each soil function using the input attributes described in Table 1. To speed-up the mapping to all grid cells, the stack of input attribute maps was divided into tiles of approximately equal size, each containing about 10,000 pixels. Each soil function model was executed with parallel processing across the tiles, and the final tiles were merged using a mosaic function to generate the soil function supply maps for the five functions.

2.4. Identification of spatial hotspots

We defined soil function hotspots as areas that provide multiple soil functions at a high level, consistent with previous definitions in ecosystem service research (Schröter and Remme, 2016). To identify these hotspots, we first converted the model outputs for each soil function (categorized as *Low*, *Medium*, or *High*) into binary maps, assigning a value of 1 to *High* supply and 0 to *Low* or *Medium* supply. We then summed the five binary maps to produce a composite hotspot map, where values range from 0 (no hotspots) to 5 (areas with high supply for all five soil functions). A similar procedure was applied to identify soil function coldspots, where a *Low* function supply was assigned to a

value of 1 and a *Medium* or *High* function supply to 0. The five binary maps were summed and range between 0 (i.e. no coldspots) and 5 (i.e. all five functions has a low supply).

2.5. Identification of spatial bundles

We identified spatial bundles and their contributing soil functions by means of cluster analysis and principal component analysis. Clustering was used to partition the set of 5 maps of soil functions' supply into groups of homogeneous and spatially disjoint clusters. We used the *k*-means algorithm (Hartigan and Wong, 1979) for this purpose, which is a widely used and computationally efficient algorithm for large datasets. In *k*-means clustering, a dataset is partitioned into a user-defined number of non-overlapping clusters by minimizing the within-cluster sum of squared errors. The within-cluster sum of squared errors is calculated with the squared Euclidean distance between each data point and the centroid of its cluster. The centroid of a cluster represents the mean of the data points within that cluster. The optimization process iteratively refines the clustering by modifying the partitions and retaining those that improve the criterion. The clustering process was repeated 100 times with a maximum of 1000 iterations. The best initialization was retained.

The optimal number of clusters was determined for a range of clusters between 1 and 50 by steps of 1 using 30 distinct statistical indices provided in the NbClust package in R (Charrad et al., 2014). The NbClust package proposes various statistical indices and method to define an optimal number of clusters. We used the Euclidean distance as the measure of dissimilarity. The optimal number of clusters was selected based on the highest Calinski–Harabasz index value.

To obtain soil function bundles, we further used an hierarchical agglomerative clustering (Ward, 1963) to evaluate the similarity between clusters. The clusters' centroids were treated as individuals. The dissimilarity between cluster centroids was quantified using Ward's minimum variance, an agglomerative clustering technique that minimizes the overall within-cluster variance. The hierarchical clustering outcome was then visualized as a dendrogram that was segmented into distinct branches, with varying colour gradients applied to allow the interpretation of the spatial distribution of soil function bundles.

Table 1

Input attributes with unit, associated reference and the soil function model in which they are involved. All variables are in projected coordinates grid cells of 1000 m × 1000 m and coordinate system Lambert Azimuthal Equal Area (EPSG:9820) and extent: 2637570 - 6523320; 1388140 - 5396890.

Variable	Unit	Reference	Function ^a
Soil			
Soil salinity	5 levels	Ivushkin et al. (2019)	PP
Rooting depth	cm	Fan et al. (2017)	PP
Available water capacity	%	Poggio et al. (2021)	WR
Soil crusting	5 classes	Daroussin et al. (1993)	WR
Organic carbon content	%	Poggio et al. (2021)	HB, CR, PP, WR
Clay content	%	Poggio et al. (2021)	HB, CR, NC, PP, WR
Silt content	%	Ballabio et al. (2019)	HB, CR, NC
Sand content	%	Ballabio et al. (2019)	HB, CR, NC
pH (in CaCl ₂ solution)	–	Reuter et al. (2008)	NC, PP
pH (measured in H ₂ O)	–	Poggio et al. (2021)	HB
Phosphorus content	mg kg ⁻¹	He et al. (2021)	NC, PP, WR
Extractable potassium content	mg kg ⁻¹	Ballabio et al. (2019)	NC, PP
Total nitrogen content	g kg ⁻¹	Poggio et al. (2021)	CR, NC, PP, WR
C:N ratio	–	Poggio et al. (2021)	HB, PP
N:P ratio	–	He et al. (2021), Poggio et al. (2021)	HB
Magnesium	mg kg ⁻¹	Négrel et al. (2021)	PP
Cation Exchange Capacity	mmol(c)/kg	Poggio et al. (2021)	PP
Bulk density	mg m ⁻³	Panagos et al. (2024)	HB, NC, PP, WR
Environment			
Groundwater table depth	cm	Fan et al. (2017)	HB, NC, PP, WR
Peatland	presence/absence	Melton et al. (2021)	CR
Natural drainage	density	Lin et al. (2021)	NC, WR
Altitude	m	Witjes et al. (2023)	PP
Slope	degree	Witjes et al. (2023)	PP
Climate			
Long-term average temperature	°C	Fick and Hijmans (2017)	HB, CR
Long-term average annual precipitation	mm	Fick and Hijmans (2017)	HB, CR, NC, PP, WR
Growing season length	number of days	EEA (2019a)	NC
Soil moisture deficit during the growing season	standard deviation from the long-term soil moisture index average	EEA (2019b)	NC, WR
Days with a daily average temperature above 5 °C	Number of days	Marchi et al. (2020)	NC, PP
Precipitation in winter	mm	Marchi et al. (2020)	WR
Precipitation during the growing season	mm	Marchi et al. (2020)	WR
Management			
Tillage	Class of tillage system	Porwollik et al. (2019)	HB
Irrigation	% area	Siebert et al. (2005)	HB, CR, NC
Artificial drainage	% area	Feick et al. (2005)	HB, CR, WR
Cover crop	% area	Fendrich et al. (2023)	CR, WR

^a HB: Habitat for Biodiversity, NC: nutrient Cycling, CR: Climate Regulation, PP: Primary Productivity, WR: Water Regulation.

Further, a principal component analysis (PCA) was used to explore the variation of spatial bundles in relation to soil function supply. In PCA, the dimensionality of the original data is reduced by transforming the original correlated variables into a smaller set of uncorrelated principal components, each is a linear combination of the initial variables. Typically, a few principal components (i.e. two or three) capture most of the variability present in the original dataset. In this study, PCA was done on the centroids corresponding to different clusters. A colour scheme was applied to visually delineate the spatial bundles, which may contain one or several clusters.

3. Results

3.1. Soil function supply

The supply of soil functions in crop and arable lands varied greatly across Europe (Fig. 2). The supply of a habitat for biodiversity, for example, was high in large patches across continental Europe (e.g. in France, Germany, and Ireland) but medium or low in the Baltic countries, in Portugal, and in the eastern part of Spain. A different pattern

is observed for nutrient cycling and water regulation, where the supply appears high or low in relatively small areas across Europe. The climate regulation function had a low supply in most of Europe, with locally high supply in a few areas such as Andalusia, Sicily, and Normandy in France. Soils providing a high supply of primary productivity were found locally across Europe, but with a gradient of progressively lower supply towards the north.

3.2. Soil function hotspots

Fig. 3 shows that land parcels defined as high in multifunctionality, i.e. those capable of simultaneously providing more than four functions at a high level, were rarely found across Europe. Such soils were identified in eastern Scotland, the agricultural regions of north-east Italy, the south of France, Slovakia, Andalusia, and Sicily. It is important to note that these occurrences were both highly isolated and spatially sparse, even within the regions mentioned. This spatial fragmentation suggests caution in interpreting these locations as true hotspots of soil multifunctionality. The map points to the emergence of localized clusters where soils tend to supply three functions. A broad

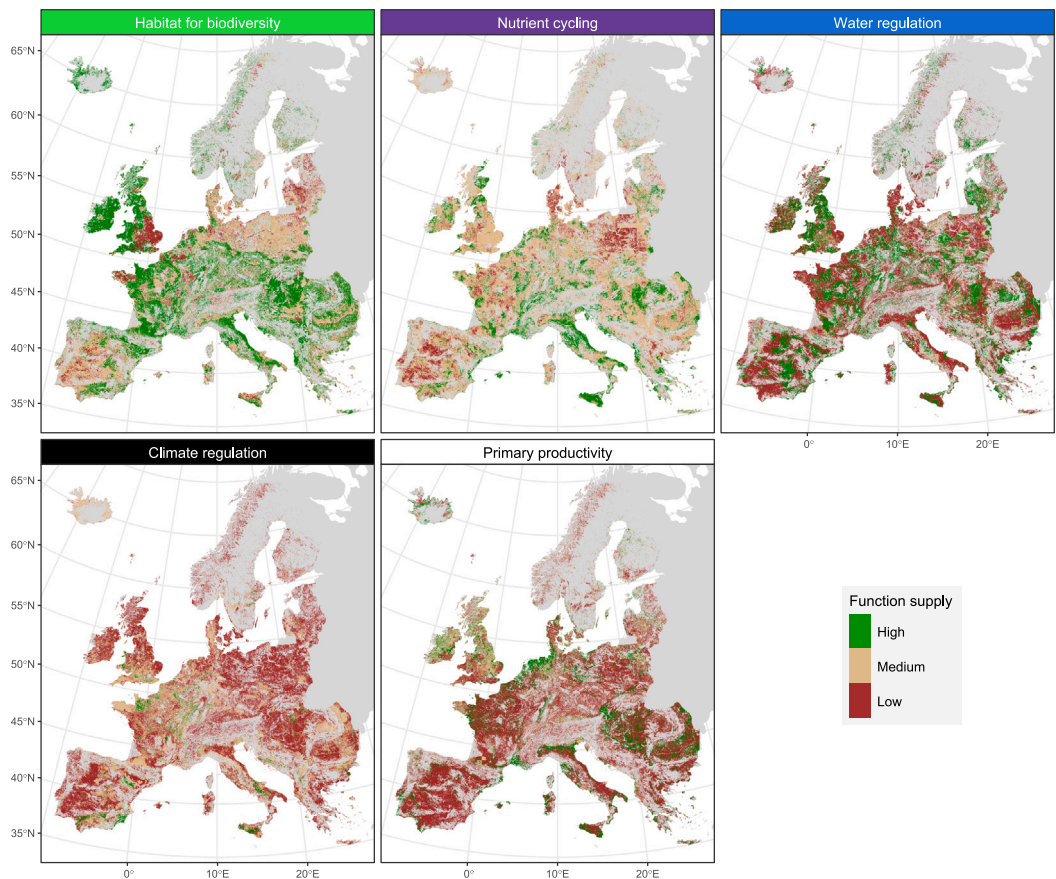


Fig. 2. Maps of the supply of the five soil functions across Europe. Grey areas are land covers not recorded as grassland or cropland, or outside the study area.

band spanning central Europe from east to west, as well as parts of north-western Europe, displayed a moderate to fairly high supply of multiple functions (i.e. 2 to 3 soil functions). In contrast, low soil function supply (i.e. fewer than 1 soil function) was observed locally in areas across all of Europe. Large areas contain no hotspots, i.e. areas with no functions providing high supply, such as in western Spain, in a large area in eastern England, in north-eastern Europe, and in the eastern part of Greece. Areas with no hotspots, shown in blue, relate well to areas with a large number of functions with a low supply (i.e. coldspots, see the Supplementary Materials).

Table 2 presents the proportion of area covered by the hotspot and coldspot classes. Most European croplands and grasslands have two or fewer hotspots, meaning that no more than two out of the five soil functions show a high supply. Only a very small fraction of the area (0.03%) exhibits a concurrent high supply across all five functions. In contrast, coldspots display a different pattern: the majority of European croplands and grasslands have between one and three coldspots, i.e. areas with a low supply for one to three of the five soil functions. A small share of the area (3.43%) shows no coldspots, meaning that none of the functions have a low supply, while areas where all five functions are simultaneously low are also very rare (i.e. less than 1%).

3.3. Spatial bundles

The optimal number of clusters for classifying spatial bundles of soil function supply was determined to be 11 using the optimal number of cluster analysis described in Section 2.5. Cluster centroids were further agglomerated and visualized using a dendrogram, revealing five groups of clusters, which were represented with a colour gradient. These groups, representing bundles of soil function supply, are shown

Table 2
Hotspots and coldspots classes, between 0 and 5, and the percentage of grassland/croplands covered by this class.

Class	Share of hotspots (%)	Share of coldspots (%)
0	25.88	3.43
1	38.97	22.02
2	26.69	40.76
3	7.60	26.41
4	0.83	6.49
5	0.03	0.88

in Fig. 4, along with the proportion of supply (i.e. low, medium, or high) for each of the five soil functions within each cluster. All together, five spatial bundles were identified (Fig. 4):

- Bundle 1 (cluster 1) is characterized by high water regulation and primary productivity, moderate nutrient cycling and habitat for biodiversity, and low or medium climate regulation.
- Bundle 2 (clusters 4, 8, and 10) has a similar pattern to the first bundle but has relatively higher habitat for biodiversity and climate regulation, yet lower primary productivity.
- Bundle 3 (clusters 3, 11, 8, and 9) has a low to medium supply of three soil functions: water regulation, primary productivity, and climate regulation, while providing a medium to high level of nutrient cycling or habitat for biodiversity.
- Bundle 4 (cluster 7) is characterized by low water regulation, habitat for biodiversity, and climate regulation, and medium to high primary productivity and nutrient cycling.
- Bundle 5 (clusters 2 and 6) features a low to medium supply of climate regulation and water regulation, with a medium to high supply of all other functions.

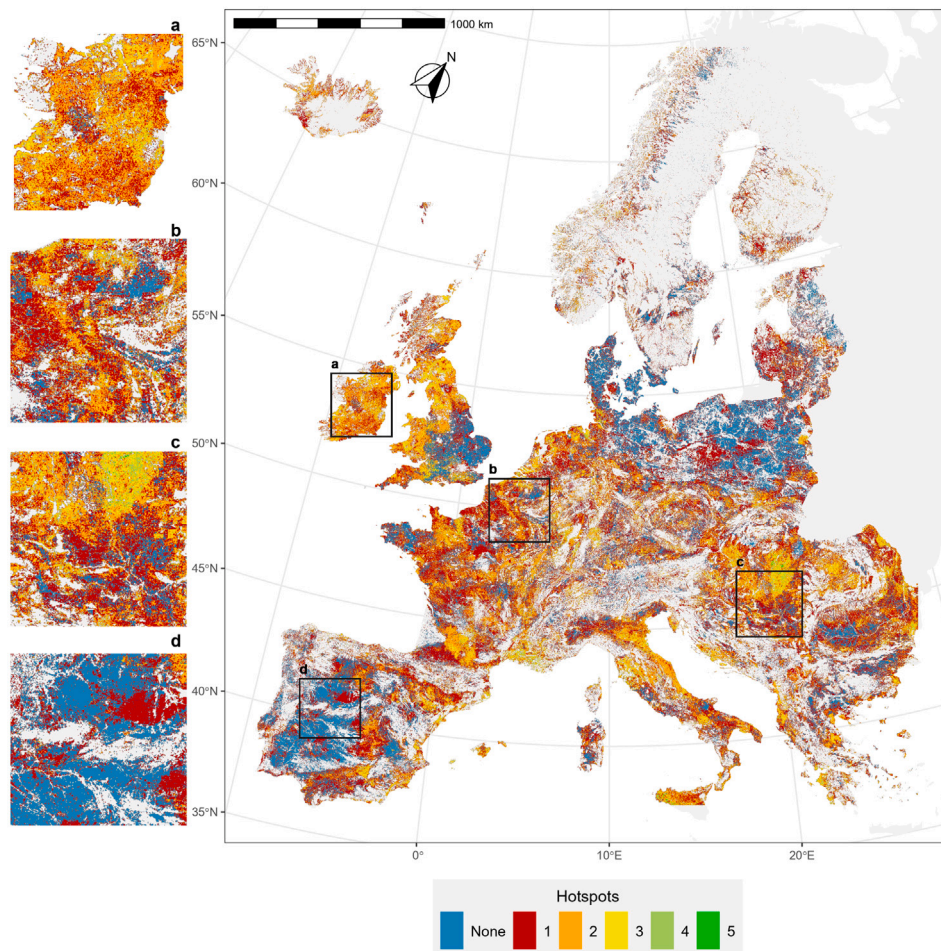


Fig. 3. Number of soil functions which are provided with high supply level (i.e. hotspots) across Europe.

PCA of the 11 clusters in relation to soil function supply is shown in Fig. 5. The first component explained 27%, while the second explained 22% of the variance among clusters, with the remaining variance unexplained. The results confirm what is shown in Fig. 4, namely that Bundles 4 and 5 (clusters 7, 2, and 5) are characterized by high primary productivity supply; Bundle 2 (clusters 4, 8, and 10) is characterized by high climate and water regulation, particularly cluster 4; while Bundle 1 (cluster 1) is characterized by moderate to high nutrient cycling. Fig. 5 also shows that climate regulation is negatively correlated with primary productivity, and that water regulation is moderately correlated with climate regulation and habitat for biodiversity. Bundle 3 (clusters 3, 11, 8, and 9) appears at the centre of the two PC dimensions and is not strongly associated with any high function supply.

Fig. 6 shows the spatial pattern of the five bundles across the croplands and grasslands of Europe. Bundle 2, shown with orangish colours, appears to be dominant in most of Europe, particularly in the central regions. Locally, we notice Bundle 3 (brownish colours), as well as Bundle 4 (greyish colours) and Bundle 5 (greenish colours), although Bundle 2 remains visually prevalent.

Table 3 shows that Bundle 2 covers the largest share of European croplands and grasslands, accounting for approximately 32% of the area. This bundle is characterized by relatively high habitat for biodiversity and climate regulation, moderate water regulation, and low values for other functions. Bundle 3 represents about 30% of European grasslands and croplands and is associated with relatively high nutrient cycling and habitat for biodiversity, and low values for other functions. Bundle 5 accounts for about 19% of the area and features relatively high primary productivity, nutrient cycling, and

habitat for biodiversity, and low values for other functions. Bundles 1 and 4 each cover around 5% of European grasslands and croplands, with Bundle 1 showing relatively high water regulation and primary productivity, moderate nutrient cycling and habitat for biodiversity, and low or medium climate regulation, and Bundle 4 having relatively high primary productivity and nutrient cycling, and low values for other functions.

4. Discussion

At the European scale, five soil function bundles were identified. Our work supports earlier studies on soil and ecosystem services interactions (e.g. Bennett et al., 2009) and supports a future assessment of soil function bundles across multiple scales. This could not only serve the scientific purpose of understanding why specific functions are bundled together and whether the association varies in space and time but also aids in the development of actions that better link human activity on soil through management (i.e. the interaction of soil functions with the socio-economic system, see Vogel et al., 2018). While this study focuses on the biophysical assessment of soil function supply, these results also provide a basis for exploring the relationship between soil functions and socio-economic demand. Establishing such links would require integrating spatial data on land use, ecosystem service needs, and policy priorities, which is beyond the scope of this paper but represents an important direction for future research.

Few existing studies have provided maps of soil functions at the European level. In this paper, we describe the spatial distribution of soil multifunctional capacity across European soils. These maps are

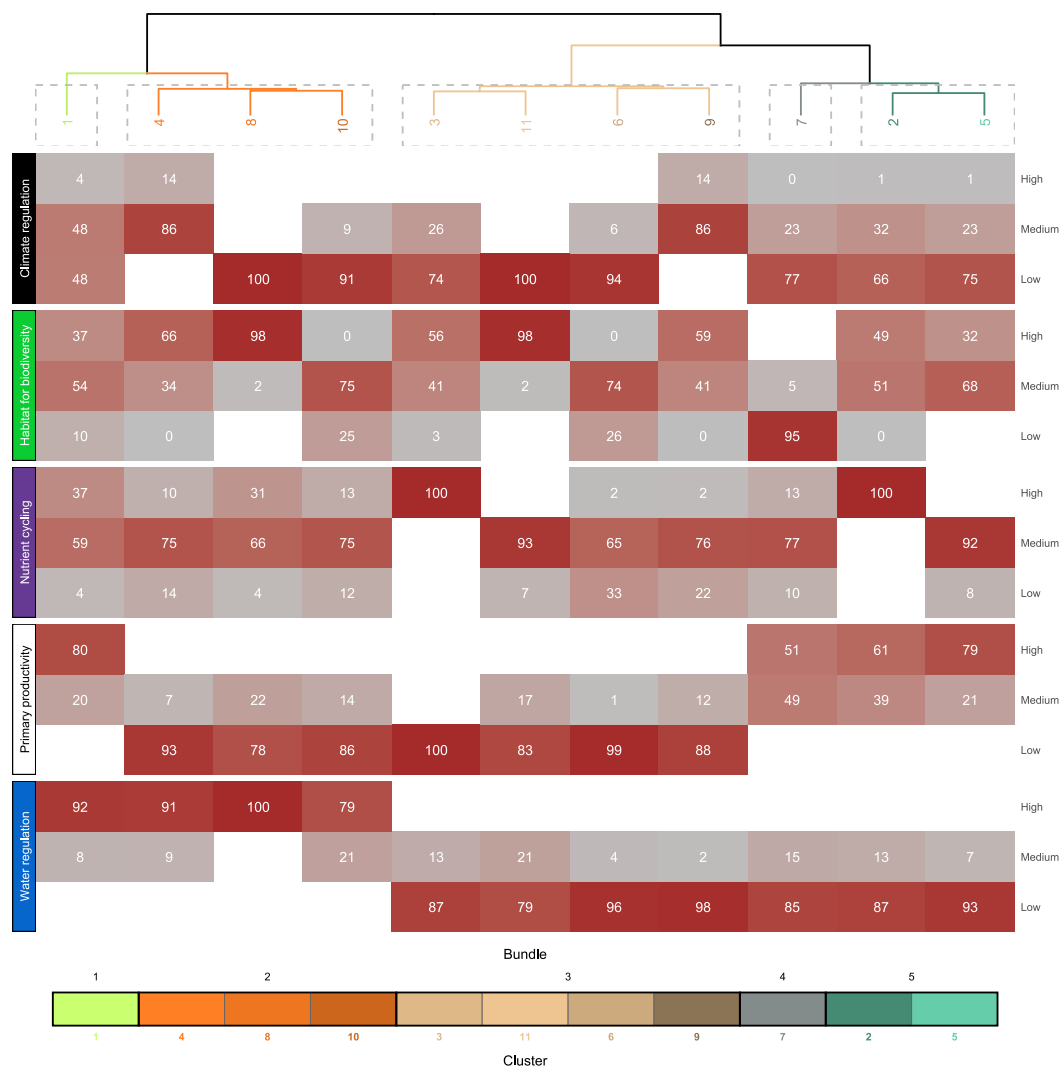


Fig. 4. Dendrogram showing the agglomeration of similar clusters into bundles of soil functions, along with the proportion of the soil function supply (i.e. low, medium or high) within the clusters, for the five soil functions. The values of x-axis at the bottom represents the 11 clusters grouped into bundles of similar colour gradients. The bundles are shown with the dendrogram of the x-axis of the upper part of the figure. The reddish colours represent the percentage of the soil function within a cluster falling in either Low, Medium or High.

based on the application of refined base models from the soil navigator, which provides an estimate of the supply of each of the five functions at low, medium or high capacity for a given location or area. Maps have not been produced before using these models and therefore direct comparison is not feasible. Another problem is the different definitions used in soil function assessment (Lechevallier et al., 2025) and the units of assessment. However, a few observations can be made and discussed in relation to the outcomes of other research where assessments of multifunctionality have been completed across many sites. Tóth et al. (2013), for example, produced maps of various soil functions at the European Union level and found a strong climate dependency between soil biomass productivity in croplands and a relationship with soil types and basic physico-chemical properties. While our models use soil types and properties as input data, we did not find a similar pattern in soil function supply for primary productivity (see Fig. 5 in Tóth et al., 2013). In another study, Vreboš et al. (2018) mapped nominal values of five soil functions whose definitions are similar to those in our work. While some of their maps (e.g. that of nutrient efficiency) compare in pattern with our maps, it is difficult to draw general conclusions on the agreement and cause of disagreement between the two studies, and we do not wish to speculate. There is clearly a need to find methodologies and techniques to validate and compare maps of

soil functions, either with existing techniques from the field of digital soil mapping (see, for example Brus et al., 2011) or by developing a new set of techniques currently lacking in soil and ecosystem services assessment (Martínez-Harms and Balvanera, 2012). Similarly, existing techniques for uncertainty propagation can be applied to quantify the overall uncertainty in model outputs (Heuvelink, 2018). This overall uncertainty is likely dominated by uncertainties in the input maps, which are typically derived from models and limited observational data.

An additional consideration concerns the temporal coverage of the datasets used in this study. The input variables listed in Table 1 were compiled from multiple European data sources collected between approximately 2005 and 2024, most of which represent long-term mean or baseline conditions rather than single-year observations. These multi-year datasets are suitable for large-scale assessments because they capture stable spatial patterns of soil and environmental properties, while smoothing short-term variability that would otherwise obscure continental trends.

Our analysis shows that most European cropland and grassland soils have a relatively low number of soil functions supplied at a high level simultaneously (Fig. 3). Soils simultaneously providing all five functions at high supply are rarely found. This could be due to errors in

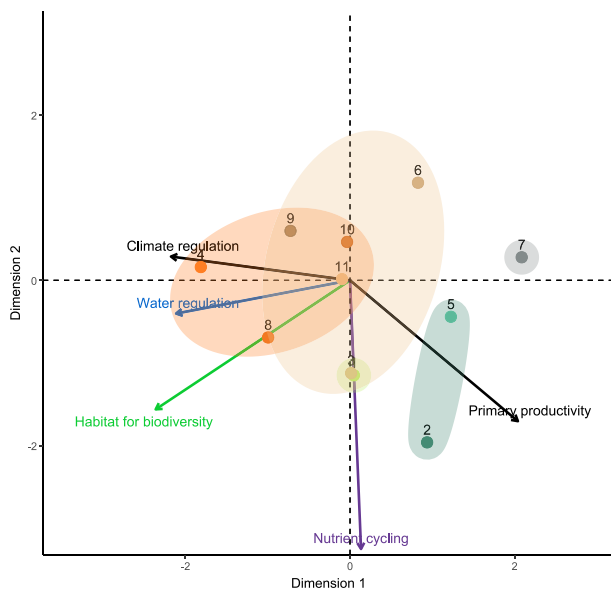


Fig. 5. Principal component analysis of the clusters in relation to the soil function supply. The dots are clusters and the coloured ellipses the bundles. The coloured arrows indicates the loadings of the principal components.

the input data or to overly broad thresholds for function fulfilment at specific locations. Soils providing three to four out of the five functions, however, are more widespread. For example, they occur for a band in western France characterized by sunflower, maize, and rye crops; the northern Pyrenees; and the grasslands and maize croplands of northern Romania and southern Hungary. This finding aligns with Zwetsloot et al. (2021), who reported similar results and suggested that achieving three out of five functions at a high level represents a realistic scenario. Rather than expecting all five functions to be delivered at a high level at every location, it may be more meaningful to consider a mosaic of soils providing three out of five functions, which collectively can deliver all five functions across larger areas. Other specific areas, however, such as the arable lands of the Eastern United Kingdom, characterized by winter wheat and oilseed/sunflower cultivation, show a remarkably low supply of multiple functions, as do the rye and potato lands of Poland and the permanent crops, barley fields, and grasslands in Spain, in a large band spanning from the north of Andalusia to the south of Castile and León and Aragón (d'Andrimont et al., 2021; Schils et al., 2022).

Although separate models were developed for cropland and grassland, visual comparison of the resulting maps (Fig. 2) revealed no clear differences in spatial patterns between the two land-use types. This is somewhat unexpected given that permanent and extensively managed grasslands are generally considered more favourable to soil function supply (Zwetsloot et al., 2021). One possible explanation is that a large proportion of grasslands in Europe are in fact intensively managed (Schils et al., 2022), and reductions in management intensity do not necessarily lead to immediate recovery of soil functions (Bakker and Berendse, 1999). Additionally, many grasslands are established on soils with intrinsic limitations—such as shallow depth, high stoniness, or low water retention capacity, that inherently reduce their potential to support certain soil functions. These pedological constraints may offset the expected benefits of grassland management practices aimed at soil conservation. We might also explain this by the fact that the hotspot map does not do justice to the individual soil function supply, meaning that different functions might be fulfilled without this being reflected in the average hotspot score.

This interpretation suggests a need to refine our conceptualization of multifunctionality. Given the rarity of soils that simultaneously supply all functions at high levels, it is necessary to consider different types

of partial multifunctionality, the so-called bundles of soil functions. This reinforces the relevance of identifying distinct combinations of functions, especially in regions where soils may support some, but not all, ecosystem services.

Our finding that the bundle 3 represented about a third of European crop and grassland soils (i.e. soils with a moderate or high supply for nutrient cycling, a relatively low supply of a habitat for biodiversity and moderate to low for all other functions) closely resembles other studies on large-scale soil function assessment. For example, Scammacca et al. (2023) found that spatial variation in soil properties can lead to moderate levels of biomass supply and water regulation, suggesting that some soils may offer moderate nutrient cycling services while providing lower levels of other functions. The question that arises is whether the suite of soil functions provided here needs to be maximized to ensure healthier soils. Several concepts (e.g. the functional land management concept of Schulte et al., 2015 or the functional soil planning concept of Bouma et al., 2012) suggest that soil function supply should be optimized rather than maximized, and this should be done in light of the spatial variation of both supply and demand. This would require a systematic approach considering the multiple trade-offs and synergies involved in soil function assessment so that the supply is balanced and met everywhere (Bouma et al., 2012). Indeed, a more systematic assessment of functions could also consider how the demand for soil function bundles by users, beneficiaries, and stakeholders varies in space, and meets the supply provided by soils. Furthermore, this demand could create conflicts between users—for example, the demand for climate regulation for policy implementation in the voluntary carbon market versus the demand for primary productivity by farmers within the same area. Since there are few, if any, “perfect” soils capable of simultaneously satisfying all stakeholder expectations. Because of that, it becomes necessary that stakeholders who need to make collective decisions and agree on which bundles of soil functions to prioritize. This highlights the importance of developing negotiation procedures and identifying the types of soil quality data needed to support these processes and inform fair, evidence-based trade-offs.

Beyond the scientific interpretation of soil function patterns, these results also have practical and policy relevance. Identifying multifunctional and low-functioning areas can help to spatially target soil management interventions and agri-environmental measures within the framework of the EU Common Agricultural Policy (CAP). Such spatial information can support regional planning by promoting sustainable land management practices that balance productivity, biodiversity, and climate regulation objectives.

5. Conclusion

We developed a methodology and produced maps of soil function supply across European cropland and grassland soils, revealing important spatial variation in the supply. Our findings indicate that a substantial proportion of these soils have a moderate nutrient cycling capacities while maintaining moderate to low levels for other functions. This pattern aligns with previous large-scale soil function assessments and shows the need for targeted land management strategies that balance trade-offs between different soil functions.

By identifying five soil function bundles, we show how soil functions interact and co-occur across diverse landscapes. The spatial distribution of these bundles suggests that soil function supply is influenced by both natural and anthropogenic factors, including land use intensity and management practices. While extensive grasslands are traditionally expected to enhance soil function supply, our results indicate that intensive management may mitigate this potential, but it needs further research. Our methodology, however, is efficient to the use of existing data. The example shown in this manuscript is, indeed, based exclusively on already-collected data.

A key challenge moving forward is the integration of soil function supply with societal demand. Different stakeholders—farmers,

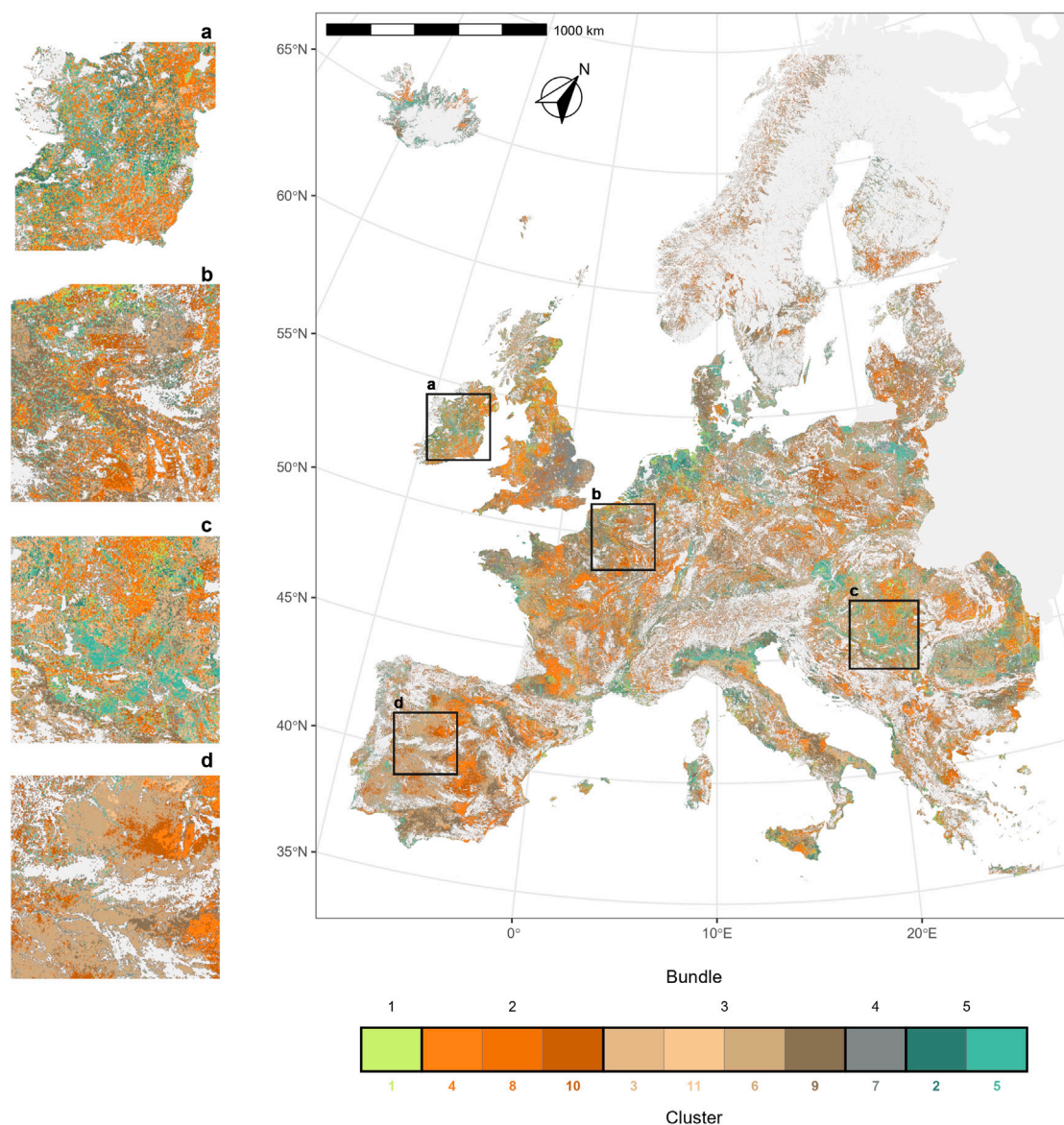


Fig. 6. Spatial representation of the soil function bundles across Europe for cropland and grassland. The boxes represent (a) Ireland and part of the United Kingdom, (b) Belgium with parts of North-Eastern France and Southern Netherlands, (c) South Hungary and Eastern Croatia and Northern Serbia, and (d) Eastern Spain and Western Portugal.

Table 3

Bundle number, surface area and share of grassland/croplands that are covered by the spatial bundles along with a description of their main characteristics.

Bundle Nb	Area (km ²)	Share (%)	Main characteristics
1	129,203	5.18	Relatively high water regulation and primary productivity, moderate nutrient cycling and habitat for biodiversity, low or medium climate regulation.
2	791,415	31.75	Relatively high habitat for biodiversity and climate regulation, moderate water regulation, and low for other functions.
3	740,785	29.72	Relatively high nutrient cycling and habitat for biodiversity, and low for other functions.
4	128,998	5.18	Relatively high primary productivity and nutrient cycling, and low for other functions.
5	481,842	19.33	Relatively high primary productivity, nutrient cycling and habitat for biodiversity, and low for other functions.

policy-makers, and conservationists prioritize different soil functions, creating potential conflicts in land management strategies. A systematic approach to soil function assessment, grounded in the principles of functional land management and soil planning, is required to ensure

that soil functions are optimized rather than maximized. This requires, in turn, a better understanding of trade-offs and synergies between soil functions and the development of tools that can effectively align soil function supply with demand across multiple scales.

The analysis presented here relies on multi-source datasets compiled over the period 2005–2024, representing long-term mean or baseline conditions. These data products are suitable for identifying stable, large-scale spatial patterns of soil function supply, although they do not capture short-term temporal dynamics. The resulting maps should therefore be interpreted as representing long-term average conditions across Europe. As more temporally harmonized and updated datasets become available, future assessments will be able to refine these maps and explore temporal changes in soil multifunctionality.

The results presented here provide a spatial basis for designing more targeted soil management and agri-environmental measures under the EU Common Agricultural Policy (CAP). Identifying multifunctional and low-functioning areas can help prioritize conservation or restoration efforts and guide sustainable land-use planning. However, the study has certain limitations, particularly the reliance on heterogeneous datasets compiled over different years. These factors may introduce some uncertainty but do not affect the overall spatial patterns identified. Acknowledging these limitations enhances transparency and provides clear direction for future improvements in data harmonization and model refinement.

Future research should focus on refining methodologies for validating and comparing soil function maps, as well as exploring new techniques for integrating soil function assessments with socio-economic considerations.

CRediT authorship contribution statement

Alexandre M.J.-C. Wadoux: Writing – original draft, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Marko Debeljak:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Philippe Lagacherie:** Writing – review & editing, Validation, Methodology, Investigation, Conceptualization. **Rachel E. Creamer:** Writing – review & editing, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.ecolind.2025.114481>.

Data availability

The authors do not have permission to share data.

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