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Modelling of Soil Multifunctionality Across Europe

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ABSTRACT

Soils sustain a number of functions playing a key role in ecosystem functioning and providing a multitude of services to human society. While it is acknowledged that all soils are multifunctional, there is, to date, limited knowledge on how the supply of soil functions and their combination differ spatially with land use type, soil characteristics, climate and land use intensity at large geographical scales. We address this gap by quantifying five functions of major importance to European soils: (1) primary productivity, (2) water regulation, (3) climate regulation, (4) nutrient cycling and (5) provision of habitat for biodiversity. We built a multi-attribute semi-quantitative model with a hierarchical structure. The model is structured for the large-scale evaluation of soil functions and takes as input a set of indicators related to dynamic and stable soil properties, as well as climate, topography and management practices, and returns qualitative aggregated attributes representing the soil functions supply. Thresholds for the soil functions supply are obtained by statistical analysis coupled with expert knowledge and vary across European environmental zones. The model is tested utilizing a large pan-European dataset focused on cropland and grassland systems. Statistical distributions of soil functions supply are obtained alongside alpha- and beta-multifunctionality representing the diversity of soil functions represented at a sampling location and the unique contribution of the sampled site to the regional (i.e. NUTS3 level) soil functions supply, respectively. We found that the supply of soil functions varied greatly across landscapes in Europe and between environmental zones. Spatial patterns of the alpha- and beta-multifunctionality revealed hotspots of multifunctionality (alpha multifunctionality) but also sites providing a set of soil function delivery unique within the region (beta multifunctionality). Few sites are both unique and highly diverse. Our study set a baseline estimate of soil functions in Europe as a prerequisite to consider soil functions in environmental planning.

1 | Introduction

The concept of multifunctional soils has gained attention in soil research and land use policy in the last decade (Bouma 2021; Kopittke et al. 2022). Soils sustain a number of functions playing a key role in ecosystem dynamics and providing a multitude of services to human society. Central to this concept is that all soils are able to provide functions (Greiner et al. 2017); they are the medium for primary productivity, regulate and purify water, mitigate climate change, support nutrient cycling and provide a habitat for biodiversity. Several recent agricultural and environmental policies have acknowledged the contribution of soils to the economic, social and cultural benefits that societies derive from the environment (Bouma 2014). In 2025, the EU proposal for a Directive on Soil Monitoring has been agreed. It aims to achieve that all soils are healthy by 2050 through maintaining or enhancing the ecosystem services provided by the soil without impairing the functions enabling those services (European Commission 2023). Similar messages addressing the need to consider and enhance soil functions are stressed in national and international organizations, for example, the Global Soil Partnership of the FAO (FAO and ITPS 2015) and through the United Nations Sustainable Development Goals of the United Nations (UN General Assembly 2015).

There has been abundant scientific literature on soil function evaluation from the pedon to the continental scale. Soil functions are estimated from measured soil properties and site conditions used as indicators of the function provision. Methods that link indicators to a function rely either on agro-environmental and biophysical model outputs or on empirical approaches with indicator scoring and empirical rules (Greiner et al. 2017). Biophysical modelling is the preferred approach as it does more justice to the mechanistic relationship between functions and indicators. One such example is the study of Choquet et al. (2021) in which a crop model was used to quantify five functions in a regional area comprising cultivated soils. There are, however, several methodological challenges for the large-scale application of process-based models; models have to date focused mostly on cultivated soils, excluding other land use types and unmanaged soils, and have assessed one or two specific functions (e.g. the soil carbon dynamic with the Roth-C model) (Choquet et al. 2021). Other problems such as model parametrization, boundary conditions and forcings have been only partly solved (Vereecken et al. 2016). Another approach is to assess the function from empirical rules, such as the water regulation function from normalized values of measured soil hydraulic saturated conductivity and air entry potential (as done in Calzolari et al. 2016). Hereafter we follow an approach commonly referred to as indicator scoring, which is usually made with thresholds defined by expert knowledge and literature harvesting (e.g. Arshad and Martin 2002). The integration of expert knowledge and existing data is made through a multi-attribute qualitative model that takes as input soil, site and management information and returns an assessment of several soil functions. To date, few such models have been developed to estimate multiple soil functions. Examples are the Integrated Valuation of Ecosystem Services and Tradeoffs model (InVEST, Sharp et al. 2014) and the Artificial Intelligence for Ecosystem Services model (ARIES, Villa et al. 2014).

The provision of multiple soil functions is referred to as multifunctionality. The multifunctionality concept has been debated (Manning et al. 2018) and characterized in multiple ways (Hölting, Beckmann, et al. 2019), but research acknowledges the necessity to move beyond the assessment of soil function hotspots at a specific scale only (Mastrangelo et al. 2014; Stürck and Verburg 2017). Hereafter, we adopt the proposal of Stürck and Verburg (2017) and the framework of Hölting, Jacobs, et al. (2019) to characterize multifunctionality by metrics similar to those used in biodiversity research and landscape ecology (e.g. richness, diversity and abundance), and to elucidate both local and regional soil multifunctionality. Such assessment at multiple scales is a prerequisite to align the soil function supply with the relevant scale of decision and policy implementation. While at the local scale, few functions answering a specific demand are usually supplied (e.g. primary productivity to support crop production) to satisfy a demand, across a regional area all functions will be required and should be feasible given changing landscape and land management conditions.

Assessing multiple soil functions and their multifunctionality on a large geographical scale is a challenging task. This is because few models designed for soil function assessment are intended for this purpose. In addition, a large amount of soil properties, site characteristics and management information is required, and are typically not available at regional or continental scales. For example, in the European Union, the largest harmonized soil survey called LUCAS, lacks soil management information and contains few soil biodiversity measurements. The assessment of large areas is further complicated by the usually significant variation in soil types, pedo-climatic zones and land uses. To date, few studies have addressed this issue, mostly focusing on relatively small datasets (e.g. Zwetsloot et al. 2021, with 94 sites across Europe), specific functions for various land uses (e.g. the primary productivity in Tóth et al. 2013), or a single function such as soil carbon storage, as in Wadoux et al. (2024). Other studies have focused on regional areas where data availability is greater using simplified proxy indicators from maps (e.g. Greiner et al. 2018). Although large-scale assessments of multifunctionality pose significant methodological and data challenges and may not provide direct, site-specific management recommendations, they are useful for the development and implementation of evidence-based EU and national strategies such as the Common Agricultural Policy and implementing the Soil Monitoring and Resilience Directive, the assessment of soil's contribution to climate change mitigation and biodiversity conservation and the identification of regions where soil functions are most at risk and where management measures would bring the greatest benefits. In addition, the large-scale assessments provide a strategic overview of the vulnerability of soil functions, highlight the greatest trade-offs and indicate the areas in most urgent need of action.

This study explores the quantification of five functions of European soils and the characterization of multifunctionality across scales, for crop and grassland land uses. The assessment of soil functions builds on the upscaled soil function assessment models presented in Wadoux et al. (2026). The models are applied to the LUCAS survey within the European Union. Multifunctionality is characterized by diversity metrics that represent the local soil multifunctionality assessment but also the unique contribution of a site to regional multifunctionality. Both local and regional multifunctionality are discussed in relation to the European Land System Archetypes as a potential driving factor of pressure on soils.

2 | Materials and Methods

2.1 | Multi-Attribute Qualitative Models

2.1.1 | Model Description

The five soil functions supply was quantified by the multi-attribute decision models of Wadoux et al. (2026) based on the DEX (Decision Expert) method (Bohanec 2022) that is implemented in the DEXi software (Bohanec 2023). A DEX model takes the form of a hierarchical decision tree composed of attributes which are aggregated by utility functions. The highest level of the tree (i.e. the most aggregated attribute) is split into a number of less complex aggregated attributes which depend

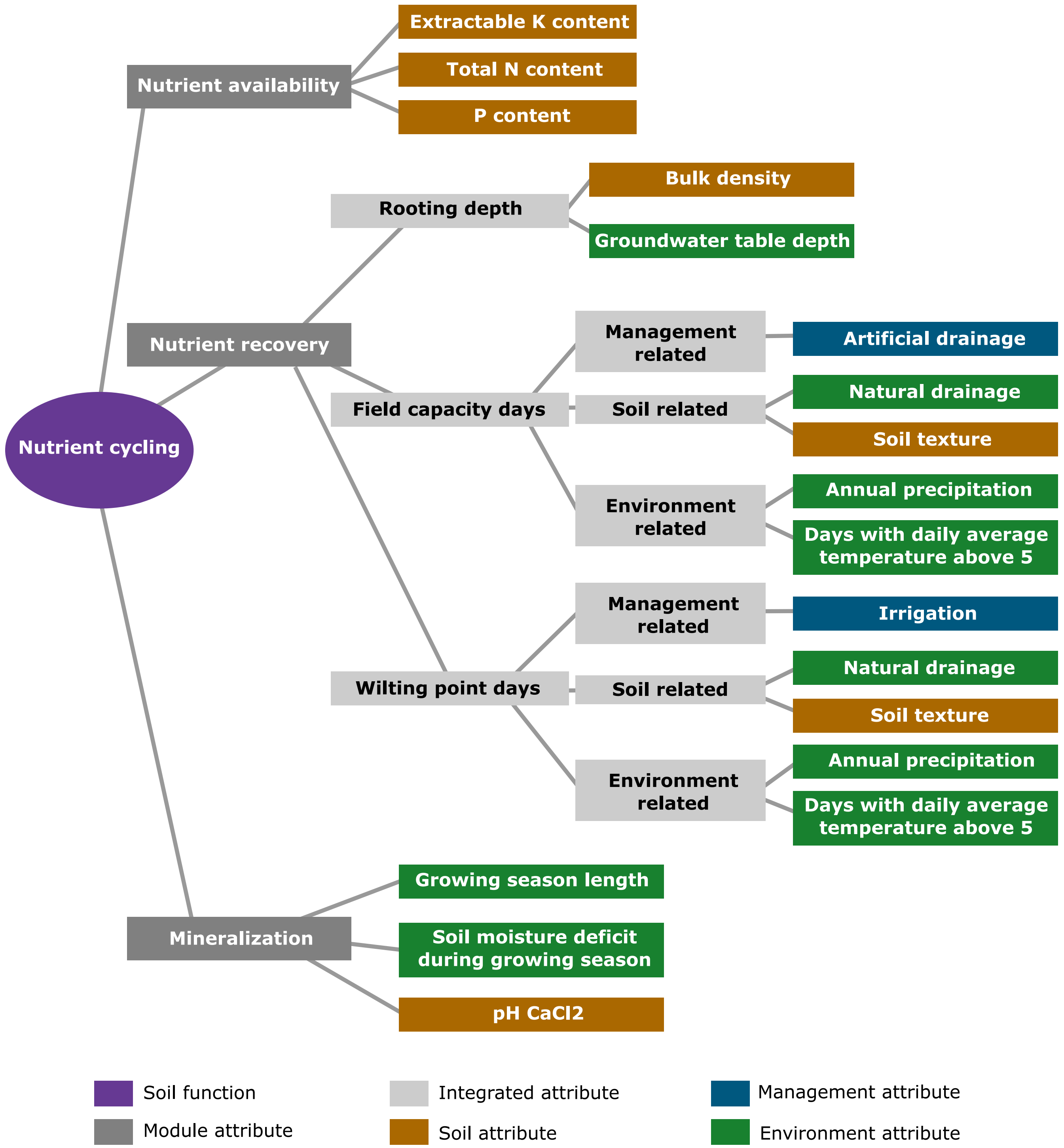

FIGURE 1 | Structure of the DEX model for the assessment of the nutrient cycling soil function from Wadoux et al. (2026).

in turn on lower-level attributes. The input attributes are continuous or categorical measurable attributes which have to be transformed into a discrete scale (e.g. *Low*, *Medium* and *High*, or *Presence* and *Absence*). Figure 1 shows an example of such a hierarchical structure for the assessment of a nutrient cycling soil function where the most aggregated attribute is the nutrient cycling soil function and the input attributes are soil, environmental and management variables. The input attributes are aggregated by the model up to the most aggregated attribute through a set of utility functions that map the values of the lower-level attributes to that of the aggregated attribute. The utility function takes the form of IF-THEN rules on the nominal values of the lower-level attributes and represented in a tabular form. The utility functions are defined by expert knowledge. The importance of attributes to the most aggregated attribute is expressed by global weights normalized between 0 (i.e. not important) and 100 (most important). The weights are approximated empirically from the entire hierarchical structure, utility functions and relative importance of every attribute. The DEX model can handle missing data by assigning the set of nominal values and testing the outcomes for each value.

2.1.2 | Model Definition

The DEX models used hereafter for the assessment of five soil functions build on the structure and utility functions defined previously 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) for the primary productivity, habitat for biodiversity, nutrient cycling, climate regulation and water regulation functions, respectively, which were refined by Wadoux et al. (2026) for their application at the regional level. This was done because the existing models were built to be incorporated into a decision support system for the field scale assessment and were unsuitable for the evaluation of functions at larger scales (e.g. regional, national and continental scales). The restructuring was done in two ways (Wadoux et al. 2026). Input attributes for which no data are available for large geographical areas (e.g. management information) or which are difficult to obtain (e.g. nitrogen inputs) were excluded from the models and replaced by easily accessible attributes. The contributions of these replaced attributes to the higher-level aggregated attributes were then assessed by examining the weights derived from the integration rules of the aggregated attributes in the DEX models. Where the resulting contributions appeared very unbalanced or scientifically inconsistent, these integration rules were modified accordingly. The final five DEX soil function models had a set of 35 soil, environmental and management input attributes. Note that several input attributes are used multiple times between the function models.

The restructured models presented in Wadoux et al. (2026) and used hereafter have module attributes (i.e. the most aggregated attribute directly linked to the functions); soil and environmental conditions for the primary productivity; nutrients, structure and hydrology for habitat for biodiversity; mineralization, nutrient recovery and nutrient availability for nutrient cycling (Figure 1); carbon storage, N_2O emissions and CH_4 emissions for the climate regulation function; water storage, water runoff and water drainage for the water regulation function. Models were built for cropland and grassland, with small differences in the management information used as input attributes.

The thresholds for the discretization of continuous variables into qualitative discrete values are obtained from expertise. All thresholds are described in Wadoux et al. (2026) and obtained either from the previous studies of Sandén et al. (2019), Van Leeuwen et al. (2019), Schröder et al. (2016), Trajanov et al. (2019), Van de Broek et al. (2019) and Wall et al. (2020), or, when not available, they were obtained with a data-driven determination: In each of the 11 European environmental zones (Metzger et al. 2012), the thresholds were obtained from the zone-specific quantiles, by assigning the nominal value of *Low* for the sites with values lower than the first quantile, the value of *High* for the sites with values higher than the third quantile and the value of *Medium* for the sites falling within the first and second quantiles.

2.2 | Soil Data

We used soil sample data from the database of the European Land Use/Cover Area frame Statistical Survey (LUCAS, Jones et al. 2020). The LUCAS database contains data from approximately 22,000 (i.e. 0–30 cm) georeferenced topsoil samples spanning 28 European countries and collected with a stratified random sampling design in 2009–2012, 2015 and 2018. About 40% of the samples were collected in cropland, 21% comes from grassland and the remaining from other land covers (i.e. mostly woodland, shrubland and bare surfaces). Soil samples are composite of five samples and have a support of 2 m radius following the sampling procedure described in Jones et al. (2020). The map of sampling location is provided in Orgiazzi et al. (2018) (Figure 1). We use the data from the 2015 survey complemented with the data from the texture analysis from the 2009/2012 survey. We used measured values of organic carbon content (in g/kg), texture (i.e. clay, silt and sand in %), pH measured in a $CaCl_2$ solution and in a suspension of soil in water, phosphorus content (in mg/kg), total nitrogen content (in g/kg) and extractable potassium content (mg/kg), the description of which and laboratory methods employed are described in Jones et al. (2020). From the measured data of organic carbon, nitrogen and phosphorus we calculated the C/N (Swift et al. 1979) and N/P ratios.

Some soil properties were not available in the LUCAS dataset but needed as input attributes in the soil function models. We therefore collected predicted values of magnesium, cation exchange capacity (CEC) and bulk density at LUCAS sampling locations. Magnesium (in mg/kg) was available in the geochemical mapping of agricultural soils and grazing land of Europe (GEMAS) dataset (Reimann et al. 2014) and was interpolated using ordinary kriging to the LUCAS sampling locations using the procedure detailed in Négrel et al. (2021). Predicted values of bulk density in T m^3 were obtained from the maps of Ballabio et al. (2016) and the CEC values (in mmol (c)/kg) from SoilGrids 2.0 predictions (Poggio et al. 2021).

2.3 | Environmental and Site Variables

The multi-attribute models (Section 2.1) take as input soil, environmental and site variables predetermined by their structure. In addition to the soil dataset, we collected 20 variables for the site and environmental conditions that are required input attributes: management, long-term climatic condition, topography and soil condition. The variables along with their reference are provided in Table 1.

All variables were reprojected to the Lambert Azimuthal Equal Area system (EPSG:9820). Continuous variables were resampled with bilinear interpolation and categorical variables with nearest neighbour. All variables conform with the same spatial extent and resolution with grid cells of 500 × 500 m.

2.4 | Analysis of Model Outputs and Interpretation

At each of the LUCAS sites, an estimate of the five soil functions is obtained. We report summary statistics of the soil function supply by environmental zone. In addition, we counted the proportion of sites that scored low or high out of the five function score values per site, for both cropland, grassland and the combined land uses (i.e. crop and grassland).

TABLE 1 | Environmental and site variables with unit, associated reference and the soil function model in which they are involved. All variables are in projected coordinates grid cells of 500 m and coordinate system Lambert Azimuthal Equal Area (EPSG:9820) and extent: 2499500E—6540000E; 1300000S—5460500S.

Variable	Unit	References	Function
Tillage	Class of tillage system	Porwollik et al. (2019)	HB
Groundwater table depth	cm	Fan et al. (2017)	HB, NC, PP, WR
Long-term average temperature	°C	Fick and Hijmans (2017)	HB, CR
Irrigation	% area	Siebert et al. (2005)	HB, CR, NC
Long-term average annual precipitation	mm	Fick and Hijmans (2017)	HB, CR, NC, PP, WR
Artificial drainage	% area	Feick et al. (2005)	HB, CR, WR
Peatland	Presence/Absence	Melton et al. (2021)	CR
Cover crop	% area	Fendrich et al. (2023)	CR, WR
Growing season length	Number of days	EEA (2019a)	NC
Soil moisture deficit during growing season	Standard deviation from the long-term soil moisture index average	EEA (2019b)	NC, WR
Natural drainage	Density	Lin et al. (2021)	NC, WR
Days with daily average temperature above 5°C	Number of days	Marchi et al. (2020)	NC, PP
Soil salinity	5 levels	Ivushkin et al. (2019)	PP
Rooting depth	cm	Fan et al. (2017)	PP
Altitude	m	Witjes et al. (2023)	PP
Slope	degree	Witjes et al. (2023)	PP
Available water capacity	%	Poggio et al. (2021)	WR
Precipitation in winter	mm	Marchi et al. (2020)	WR
Soil crusting	5 classes	Daroussin et al. (1993)	WR
Precipitation during growing season	mm	Marchi et al. (2020)	WR

Abbreviations: CR, climate regulation; HB, habitat for biodiversity; NC, nutrient cycling; PP, primary productivity; WR, water regulation.

2.4.1 | Alpha- and Beta-Multifunctionality

We assessed the multifunctionality of soils across scales by calculating the alpha- and beta-multifunctionality. Alpha-multifunctionality was defined as the diversity of soil functions supply at a site, whereas beta-multifunctionality was defined as the unique site-specific contribution of soil functions supply to the regional soil functions supply. We followed the definitions and approaches of Hölting, Beckmann, et al. (2019) in which alpha and beta multifunctionality are independent one from another.

Alpha-multifunctionality was calculated with the inverse of the Simpson's diversity index, given by:

$$\text{Simpson's diversity} = 1 / \sum_{i=1}^{F} p_i^2 \tag{1}$$

where F is the number of soil functions considered at a LUCAS site and p_i is the proportion of the ith function supply to the total supply of soil functions at the site. The alpha-multifunctionality is a metric that accounts for the richness of functions, their abundance and their relative supply. Using the inverse of the Simpson's diversity corresponds to the Hill diversity number of order 2 (Jost 2006). Values range from 0 to 5 (i.e. the 5 functions are supplied at their maximum) where values close to 0 indicate low multifunctionality and values close to 5 high multifunctionality. Prior to the calculation we converted the qualitative model output values *Low*, *Medium* and *High* into the quantitative values of 0, 0.5 and 1, respectively. The diversity function of the vegan (Oksanen et al. 2007) package in R (R Core Team 2023) was used to calculate the Simpson's index.

Beta-multifunctionality was obtained by calculating the total abundance-based dissimilarity between all sites within the NUTS3 region (EUROSTAT GISCO 2023). The dissimilarity was calculated with the Bray–Curtis metric (Bray and Curtis 1957) obtained by $BD_{ij} = 1 - \frac{2C_{ij}}{S_i + S_j}$, where i and j are two sites within the NUTS3 region, S_i and S_j are the summed supply of soil functions at the ith and jth sites, respectively, and C_{ij} is the sum of the smallest supply of soil functions for each function between the ith

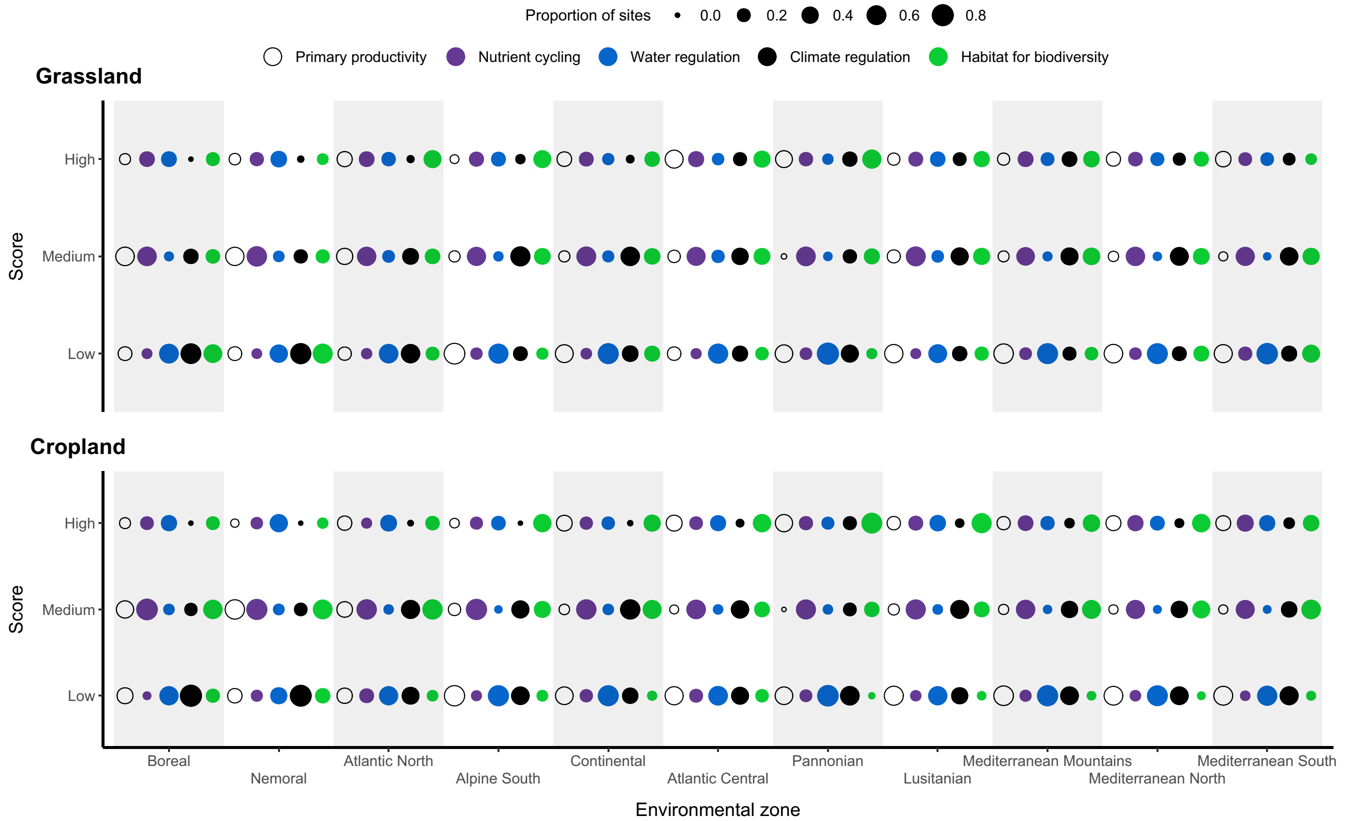

FIGURE 2 | Soil function supply at LUCAS location in the environmental zones, for grassland and cropland. The colour indicates the function and the size of the bubble indicates the proportion of sites with a score (i.e. either *Low*, *Medium* or *High*).

and *j*th sites. Beta-multifunctionality if obtained by averaging the dissimilarity between a LUCAS site and all LUCAS sites within the respective NUTS3 region using the same values of functions used to calculate the alpha. Beta accounts for both diversity and abundance. Values range between 0 and 1 where 0 indicates low and 1 indicates high beta-multifunctionality. We used the beta.pair.abund function from the betapart (Baselga and Orme 2012) R package to calculate the dissimilarity.

For visualization purposes, alpha- and beta-multifunctionality values were reclassified into a bivariate nine colour-scale corresponding quantiles. The nine colour classes were then linked to the European Land System Archetypes (LSA, Levers et al. 2018). The LSA map is an indicator of the pattern of land use and land use intensity. It contains 15 classes throughout the European Union, obtained by clustering 12 land use indicators for the year 2006. We calculated the proportion of each of the nine alpha- and beta-multifunctionality classes falling within the LSA. In our study we covered 12 of the 15 LSA classes because we focused on grassland and cropland.

3 | Results

3.1 | Patterns of Soil Functions Supply

Figure 2 shows the estimate of soil functions supply at the 22,009 LUCAS locations, aggregated by environmental zones and land use. We observe (i) substantial variation in the supply of the five functions within environmental zones, (ii) moderate difference in soil functions supply between environmental zones and (iii) minor difference in the soil functions supply between cropland and grassland (Figure 2). For all environmental zones, it appears that most soil function supply is either low or medium. In the continental zone, for example, primary productivity and water regulation were most commonly provided with a low score in both grassland and cropland, nutrient cycling, climate regulation and habitat for biodiversity had a majority of medium supply in both land use types. A similar pattern of soil function supply is observed in most zones. Strikingly, sites in the Boreal zone performed poorly in climate regulation (i.e. most sites have a low function supply), whereas in the Panonian zone primary productivity scored high, which supplied primary productivity and biodiversity at a high level.

Figure 3 shows that nearly all sites scored low for one (27%), two (40%) or three (23%) soil functions. A different pattern is observed for sites with a high supply of functions, where most sites (i.e. 41%) had a single high score for the five functions. Few sites had low scores for most functions, and no site had a low score for all five functions. Likewise, very few sites had a high function supply for four functions and no site had the five functions scored as high. Cropland and grassland had generally a similar pattern in the proportion of low and high scores, but cropland had more sites with two and three functions scored as low, whereas a slightly higher number of grassland sites scored high for four functions compared to the cropland sites.

3.2 | Patterns of Alpha- and Beta-Multifunctionality

The diversity of soil function supply at LUCAS locations varied greatly (Figure 4, left side) but without a clear continuous latitudinal or longitudinal pattern across Europe. Regions of low (i.e. <2) alpha-multifunctionality were found in patchy areas throughout Europe, including regions such as Southern England, Denmark, North-West and central France, Bulgaria, the southern part of Romania, and the centre of Spain and Italy, as well as Corsica, Sardinia and the southern Greek islands.

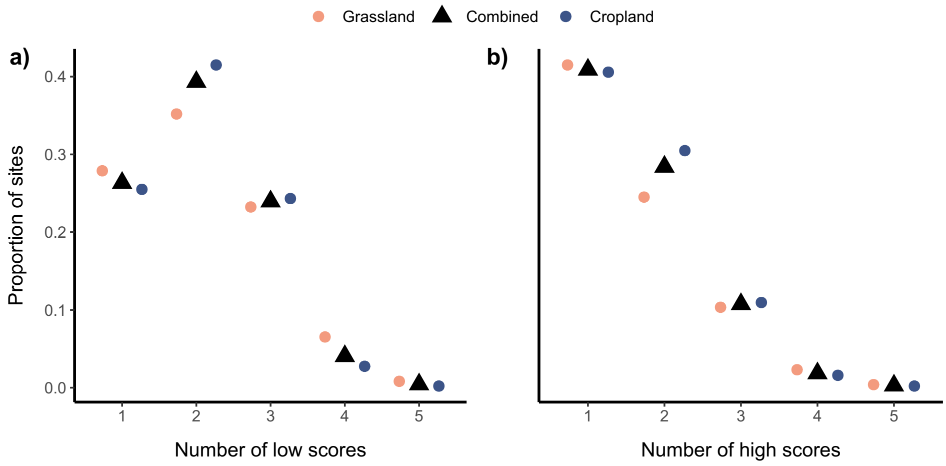

FIGURE 3 | Proportion of sites with (a) low and (b) high soil function supply score. The coloured dots indicate the land use type, either grassland or cropland, whereas the black triangle indicates the combination of the two land uses.

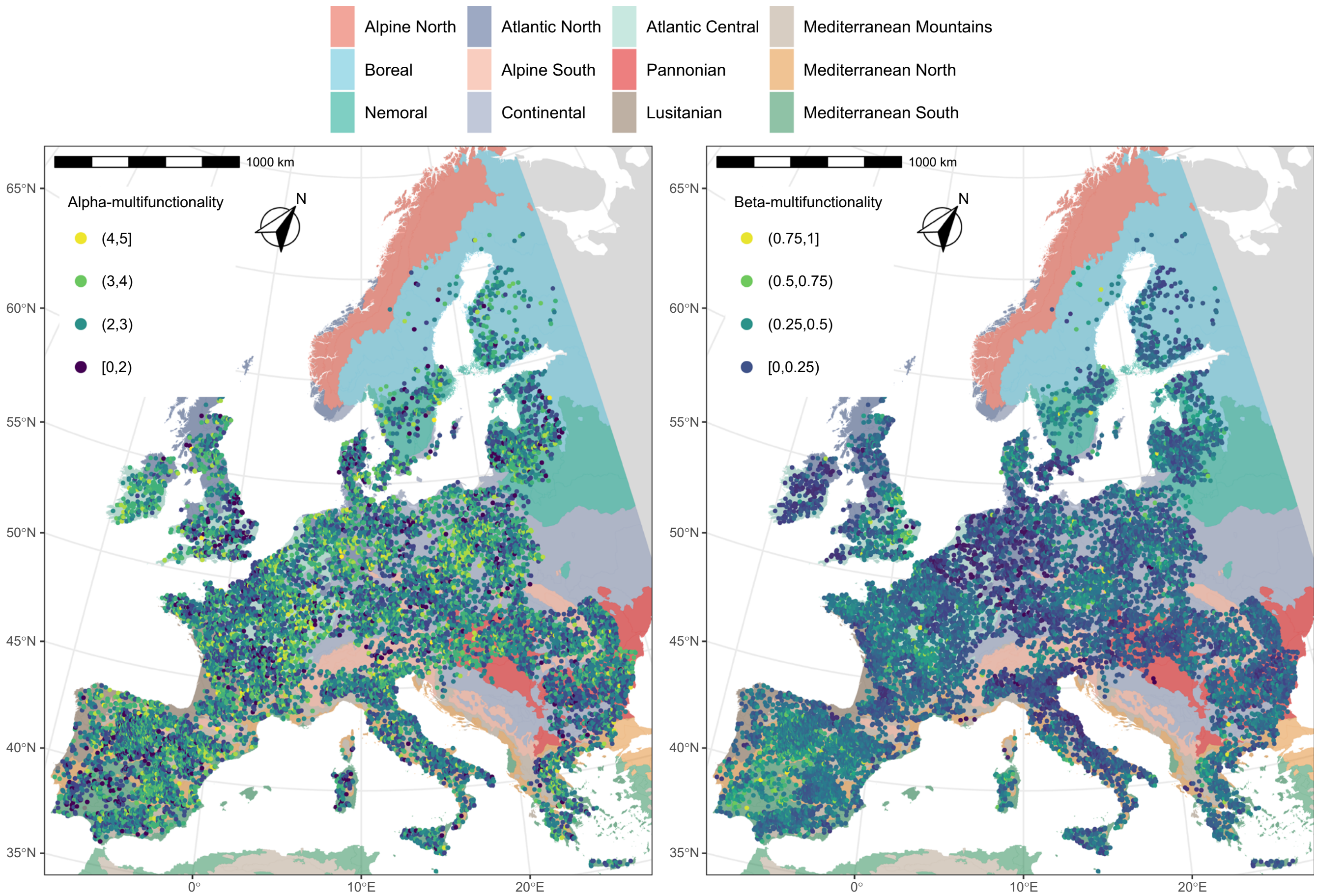

FIGURE 4 | Alpha (left) and beta (right)-multifunctionality. Alpha-multifunctionality is measured by the inverse of the Simpson's diversity index and represents the diversity of soil function supply at the LUCAS locations. Beta-multifunctionality is measured by the total-based dissimilarity between all sites within the NUTS3 region and the LUCAS point. The colours for beta show the unique supply of soil function relative to the NUTS3 supply of functions, between one and five functions. The colours indicate the number of functions supplied at a high level, between one and five functions. The background colour refers to the environmental zones of Metzger et al. (2012).

Regions of high (i.e. >4) alpha-multifunctionality were found in Ireland, central Poland, and in a band spanning from the south of the Netherlands to the western part of Switzerland. There appears to be no clear relationship between the environmental zones (see also the Supporting Information) and the level of alpha-multifunctionality, although some marked boundaries appear locally, such as in the north of Ireland between the Atlantic North and Atlantic Central zones, with higher alpha levels in the latter, or between the Nemoral and Boreal zones around Lithuania and Latvia, with higher alpha in the former.

The map of beta-multifunctionality (Figure 4, right side) showed a smooth spatial pattern with marked differences between regions. Soils delivering unique contributions to soil functions (i.e. with beta-multifunctionality >0.5) were found in patches in southern Sweden and the United Kingdom, in central France, in a small area at the border between Poland and the Czech Republic, and in the southwestern part of Spain. Low contributions of the sites to regional multifunctionality (i.e. with low beta-multifunctionality), conversely, were found in Ireland, most of Germany, Belgium, the Netherlands and the northern coast of Italy. As with alpha, there was no clear relationship between the environmental zones and the values of beta.

Figure 5 shows the composite alpha- and beta-multifunctionality index at LUCAS locations, and represents sites with various combinations of diversity and uniqueness in soil function supply. A clear pattern is identified. Several regions in Europe were found to provide multiple functions (i.e. with high alpha-multifunctionality), but they exhibit low regional uniqueness (i.e. low beta-multifunctionality). This is the case, for example, in a large band spanning from the Netherlands to Switzerland. Most of northern France, Spain and southern England, conversely, show areas with unique sites but low alpha-multifunctionality. Few specific locations have both high diversity and uniqueness. A summary of the most important areas with a combination of alpha- and beta-multifunctionality is provided in Table 2.

3.3 | Alpha- and Beta-Multifunctionality in Relation to Land System Archetypes

To explore the relationship between land system archetype intensity and multifunctionality, we sorted the archetypes by intensity and calculated the proportion of LUCAS sites within each composite of alpha- and beta-multifunctionality, as shown in Figure 6. Overall, no clear pattern was observed between management intensity and the presence of alpha- and beta-multifunctionality coldspots or hotspots, except in the case of high-intensity croplands. Across all land system archetypes, coldspot and hotspot sites were found in similar proportions. In high-intensity croplands, that is, in the class with the highest management intensity, however, the proportion of sites having both low alpha- and beta-multifunctionality, or medium alpha- and low beta-multifunctionality, was significantly higher compared to other archetypes.

The breakdown of Figure 6 by environmental zone (see Supporting Information) reveals a more nuanced pattern. Note that only LSA classes with more than 20 observations were kept. A latitudinal gradient appears to influence the proportion of coldspot and hotspot alpha- and beta-multifunctionality sites. In northern latitudes, extending to the Alpine South zone, high-intensity land system archetypes—such as large-scale permanent croplands and high-intensity arable croplands—show a higher proportion of sites with high beta- and low alpha-multifunctionality. In contrast, for lower-intensity systems, such as low-intensity grasslands or mosaics, there is a trend of decreasing beta-multifunctionality and increasing alpha-multifunctionality. An inverse pattern is observed in Southern Europe, particularly in Mediterranean zones. Here, high-intensity systems are associated with high alpha- and low beta-multifunctionality, but as management intensity increases, there is a gradient of rising beta- and decreasing alpha-multifunctionality.

4 | Discussion

The soil function assessment across the LUCAS locations revealed a marked spatial pattern in soil function supply. While nearly all sites delivered more than one function with a high or medium score, some regions (e.g. Southern Ireland, Eastern France, Central Poland) clearly scored high in multiple soil functions. About 15% of the sites were delivering three functions at high levels in Europe. About 26% of the sites, conversely, were delivering low scores of at least three functions. A similar imbalance in the supply of the various soil functions was found by others in European (Zwetsloot et al. 2021), national (Vazquez et al. 2021) and regional (Rabot et al. 2022) cases. The spatial differences in the assessed soil functions reflect variations in the values of the underlying input attributes, and while a systematic meta-analysis of the model outputs could provide detailed causal explanations, such an analysis was beyond the scope of the present study and represents a promising direction for future research.

While our assessment shows important differences in soil function supply between regions, we did not find significant differences between environmental zones or between croplands and grasslands. The lack of a clear difference between environmental zones is difficult to explain. The small difference that we found between grasslands and croplands is probably due to the restructuring of the field-scale models to the regional level, which directly affected the set of input attributes that were initially used to differentiate croplands from grasslands. We acknowledge that the model upscaling led to a less distinct separation between the cropland and grassland soil function models, but it is difficult to assess whether this small difference is due to the removal of management variables or the accuracy of the soil and environmental attributes used as input to the two models.

All countries had at least a few hotspots of soil function supply, characterized by highly diverse and unique sites. However, the distribution of these sites across agricultural areas was highly variable in Europe. Agricultural regions in France, Spain, Poland and Romania contained a large number of diverse and unique sites, indicating their significant role in soil functions supply. In contrast, the Netherlands and parts of Germany had fewer sites supporting multiple functions. Hotspots of soil functions were closely linked to management systems: high-intensity

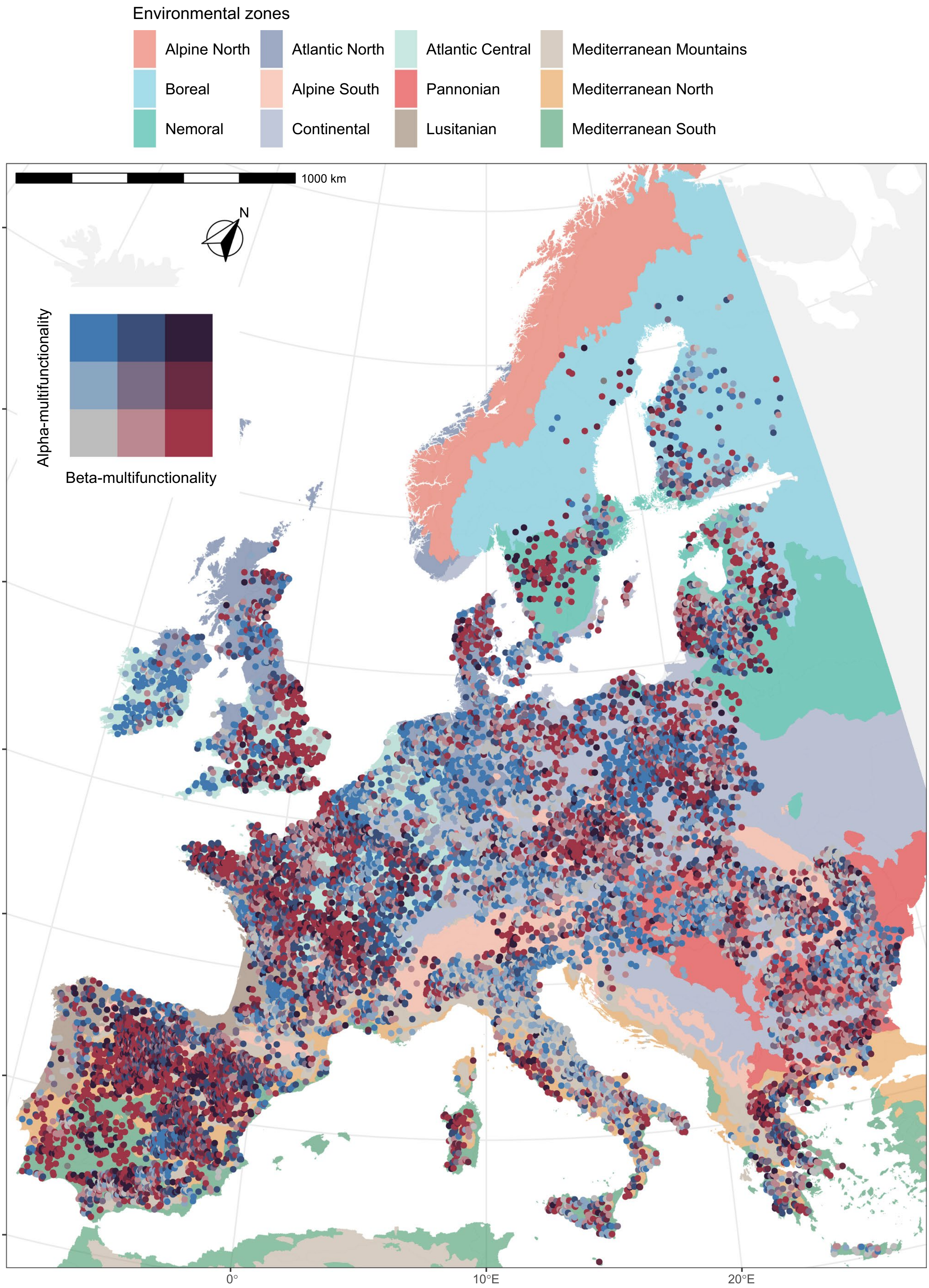

FIGURE 5 | Legend on next page.

FIGURE 5 | Composite classes of alpha- and beta-multifunctionality at LUCAS locations. The bivariate colour scheme was obtained based on quantiles for the class intervals for alpha of [1, 2.67], (2.67, 3] and (3, 5] and for beta of [0, 0.294], (0.294, 0.389] and (0.389, 0.984]. The background colour refers to the environmental zones of Metzger et al. (2012).

TABLE 2 | Combination of alpha- and beta-multifunctionality along with their values, interpretation and example regions where the combination occurs.

Combination	Values	Description	Example regions
High alpha, high beta	alpha > 4, beta > 0.39	Highly diverse and unique	Southern Sweden, Slovakia, Central France, Central Spain, Southern England
High alpha, low beta	alpha > 4, beta < 0.29	Highly diverse but not unique	Ireland, Northern England, Western Belgium, Southeastern Poland, Northern Germany, Northern Croatia
Low alpha, high beta	alpha < 2.67, beta > 0.39	Not diverse but unique	Southeastern England, Denmark, Brittany, Central Spain, Southern Portugal, Sardinia, Northern Greece, Northern Latvia
Low alpha, low beta	alpha < 2.67, beta < 0.29	Not diverse and not unique	The Netherlands, Northern coast of Italy, Eastern Germany, Northeastern Poland, Northern Romania

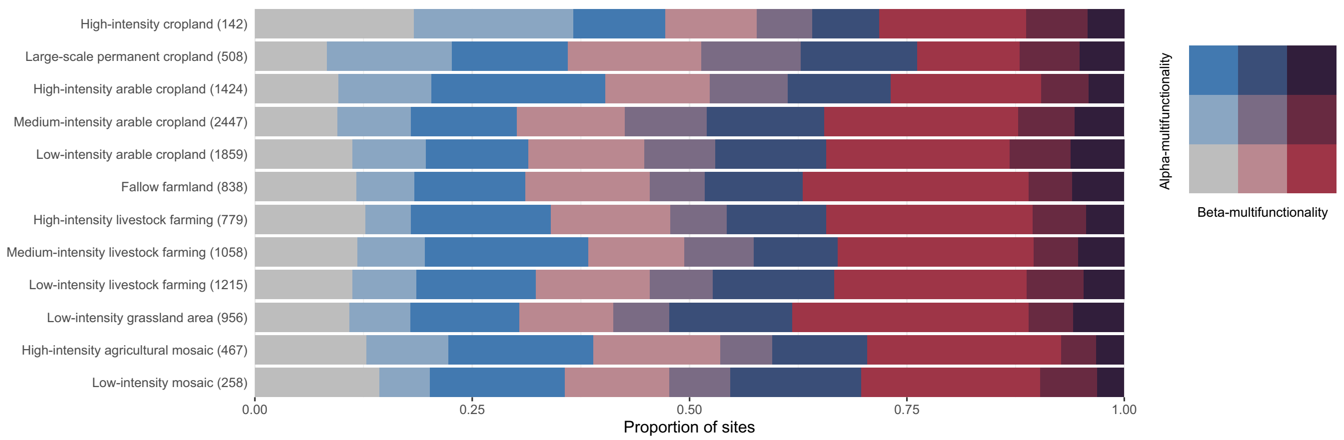

FIGURE 6 | Proportion of sites for each composite class of alpha- and beta-multifunctionality in relation to 12 land system archetypes. The numbers adjacent to each land system archetype class indicate the number of sites within that class. Colours represent the composite alpha- and beta-multifunctionality classes, using the same colour scale as in Figure 5. The land system archetypes are arranged in order of management intensity, as described in the Supporting Information of Levers et al. (2018).

croplands generally showed more coldspots, though this varied across environmental zones. This suggests that the interaction between management intensity and environmental conditions is a key driver of soil function supply. While further assessment is needed to validate the relationships identified with the LUCAS dataset, the findings suggest that tailored management solutions could be developed for specific environmental zones.

We demonstrated that assessing soil functions is feasible for large geographical areas. While many studies have focused on assessments at the field scale (e.g. Vogel et al. 2019) or regional scale (e.g. Rabot et al. 2022), this is, to our knowledge, the first attempt to estimate multiple soil functions using data from the LUCAS soil survey. Large-scale assessments are often limited by the absence of key soil attributes essential for evaluating soil functions. As van Leeuwen et al. (2017) pointed out, the current LUCAS survey emphasizes chemical and physical soil properties, often overlooking biological parameters. Although there has been progress in collecting more management-related and biological data (see Jones et al. 2021), comprehensive datasets at large scales are still lacking. In this study, we supplemented missing data with existing maps. While not ideal, this approach enables an initial assessment that can be refined as more accurate data become available in the future.

The models applied in this study highlight not only the potential for function optimization through the improvement of some specific input attribute values (e.g. the organic carbon), but also the importance of considering the regional scale when evaluating overall function supply. Soil multifunctionality (i.e. alpha- and beta-multifunctionality), indeed, seems to appear in all regions. Very few sites, conversely, contain a high supply of all five functions. These results could complement regional models by providing a broader strategic context and identifying regions where soil functions are underperforming and where potential trade-offs or synergies between functions are particularly pronounced, providing guidance on where more detailed regional models can be most effectively applied. Moreover, this modelling can support the assessment of soil health and ecosystem services. The European Commission's recent proposal for a Directive on Soil Monitoring and Resilience (European Commission 2023) aligns with this approach, advocating for sustainable soil management that enables the supply of ecosystem services without compromising soil functions.

A key next step is to link soil function supply to the corresponding demand. While our results show significant spatial variability in function supply, there is also considerable variability in demand across the EU, as highlighted by Schulte et al. (2019). Connecting these two aspects would offer a more nuanced understanding of the current levels of soil function supply, both locally and regionally and help identify areas of spatial mismatch where high demand is not met by high supply (Schirpke et al. 2019). This could prove to be a substantial addition to forthcoming soil health research and aid in implementing policies on a supra-regional and cross-national scale.

5 | Conclusions

We quantified multiple soil functions across Europe using the LUCAS survey and the multi-criteria decision model designed for the large-scale assessment of soil functions. We show that soil function assessments at large geographical scales are possible, despite challenges related to data gaps, particularly for biological parameters and management information. From the results and discussion we draw the following conclusions:

- There is significant spatial variability in soil function supply, with regions like Southern Ireland, Eastern France and Central Poland scoring high in multiple functions, while other areas exhibit low supply across several functions. These patterns highlight the influence of both environmental conditions and management intensity, which supports the need for more local analyses to confirm these results.
- The assessment found no significant differences in soil function supply between croplands and grasslands or between environmental zones. This lack of distinction may be due to limitations in the models or data used, particularly the absence of detailed management variables.
- Soil multifunctionality, as characterized by alpha- and beta-multifunctionality, was nearly always present in a few sites at regional level, whereas few sites were able to provide a high function supply to all five functions. This shows that while all soil can provide soil functions, soil multifunctionality should be considered at the regional level.
- A next step is to link the spatial variability in soil function supply to the demand for these functions, as this would help identify mismatches and optimize function supply regionally. This approach could inform future soil health studies and guide policy development at supra-regional and cross-national levels.

Overall, this study is a first step towards regional soil function optimization considering the local supply and synergies and trade-offs. We envision future application in soil function monitoring within the frame of the future Soil Monitoring and Resilience Directive of the European Union.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from EUSO. Restrictions apply to the availability of these data, which were used under license for this study. Data are available from the author(s) with the permission of EUSO.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** sum70147-sup-0001-DataS1.pdf.