Received: 28 January 2020 | Revised: 16 September 2020 | Accepted: 17 September 2020

DOI: 10.1111/ejss.13051

SPECIAL ISSUE ARTICLE

European Journal of Soil Science WILEY

Soil multifunctionality: Synergies and trade-offs across European climatic zones and land uses

Marie J. Zwetsloot[1] | **Jeroen van Leeuwen**[2] | **Lia Hemerik**[2] | **Henk Martens**[1] | **Iolanda Simó Josa**[1,3] | **Marijn Van de Broek**[4] | **Marko Debeljak**[5] | **Michiel Rutgers**[6] | **Taru Sandén**[7] | **David P. Wall**[8] | **Arwyn Jones**[9] | **Rachel E. Creamer**[1]

[1]Soil Biology Group, Wageningen University, Wageningen, The Netherlands

[2]Biometris, Wageningen University, Wageningen, The Netherlands

[3]Smart Soil & Land, Lleida, Spain

[4]Department of Environmental Systems Science, Swiss Federal Institute of Technology, ETH Zürich, Zürich, Switzerland

[5]Department of Knowledge Technologies, Jozef Stefan Institute, Ljubljana, Slovenia

[6]Centre for Sustainability, Environment and Health, National Institute for Public Health and the Environment, Bilthoven, The Netherlands

[7]Department for Soil Health and Plant Nutrition, Austrian Agency for Health and Food Safety, Vienna, Austria

[8]Crops, Environment and Land Use Programme, Teagasc, Johnstown Castle, Wexford, Ireland

[9]Land Resource Management / SOIL action, European Commission, Joint Research Centre, Ispra, Italy

Correspondence

Marie J. Zwetsloot, Soil Biology Group, Wageningen University, Wageningen, The Netherlands.
Email: marie.zwetsloot@wur.nl

Funding information

Horizon 2020 Framework Programme, Grant/Award Number: 635201

Abstract

With increasing societal demands for food security and environmental sustainability on land, the question arises: to what extent do synergies and trade-offs exist between soil functions and how can they be measured across Europe? To address this challenge, we followed the functional land management approach and assessed five soil functions: primary productivity, water regulation and purification, climate regulation, soil biodiversity and nutrient cycling. Soil, management and climate data were collected from 94 sites covering 13 countries, five climatic zones and two land-use types (arable and grassland). This dataset was analysed using the Soil Navigator, a multicriteria decision support system developed to assess the supply of the five soil functions simultaneously. Most sites scored high for two to three soil functions, demonstrating that managing for multifunctionality in soil is possible but that local constraints and trade-offs do exist. Nutrient cycling, biodiversity and climate regulation were less frequently delivered at high capacity than the other two soil functions. Using correlation and co-occurrence analyses, we also found that synergies and trade-offs between soil functions vary among climatic zones and land-use types. This study provides a new framework for monitoring soil quality at the European scale where both the supply of soil functions and their interactions are considered.

Highlights

- Managing and monitoring soil multifunctionality across Europe is possible.
- Synergies and trade-offs between soil functions exist, making it difficult to maximize the supply of all five soil functions simultaneously.
- Synergies and trade-offs between soil functions vary by climatic zone and land-use type.
- Climate regulation, biodiversity and nutrient cycling are less frequently delivered at high capacity.

KEYWORDS
arable land, climate, grassland, monitoring, soil multifunctionality, synergies, trade-offs

1 | INTRODUCTION

Agricultural land provides a multitude of soil functions to society. With an 80% probability that the world population will reach between 9.6 and 12.3 billion in 2100 (Gerland et al., 2014), the demand for global food security and associated pressure on soil to sustain the production of food, feed, fibre and fuel is rising (Lal, 2009). Although soils are mainly considered for their role in supporting primary productivity, agricultural and environmental policies call for the protection, restoration and enhancement of other soil functions, including the supply of clean water, nutrient recycling, climate change mitigation and the provision of a habitat for biodiversity (Schulte et al., 2014). For example, through the European Union (EU) Nitrates Directive (European Economic Community, 1991), water bodies and soil management practices are under close monitoring and regulation to reduce water pollution from agricultural nitrates. The 2030 Climate and Energy Framework (European Commission, 2014) and the COP21 Paris Agreement (UN, 2015) emphasize the crucial role of soils in carbon sequestration to reduce the atmospheric CO_2 concentration. This same message is stressed by the recently published Green Deal for Europe (European Commission, 2019), which "places soil management at the heart of initiatives for a climate neutral Europe and a pollution-free environment" by 2050, together with new initiatives to address the main drivers of biodiversity loss and a "Farm to Fork" strategy to deliver a green and healthier agriculture system. Under the future Common Agricultural Policy (CAP), environmental and climate action will also receive greater emphasis (European Commission, 2018), with three out of the nine objectives directly linked to soil functions: (a) climate change mitigation and adaptation, (b) sustainable management of natural resources and (c) protection of biodiversity. By means of Strategic Plans, the new CAP will allow for greater flexibility at the national and regional level so that Member States can work with farmers to select the most suitable measures for their land to achieve the EU objectives (European Commission, 2018). Considering this enhanced focus on soil in the future framework of the CAP and the rising societal demand for food security and environmental sustainability, questions arise about how we can assess the supply of soil functions across Europe and to what extent synergies and trade-offs between soil functions exist across different land-use types and climatic zones.

Monitoring soil functions is closely linked to soil quality assessment. The development of soil quality as a concept and selection of indicators are thoroughly discussed in the review by Bünemann et al. (2018). Although the first papers on soil assessment or land evaluation evaluated soil quality based on inherent and/or static properties (Klingebiel & Montgomery, 1961; Martel & Mackenzie, 1980; Mausel, 1971; Storie, 1933; Verity & Anderson, 1990), soil quality assessment has evolved to include more dynamic soil indicators responsive to management (Karlen, Ditzler, & Andrews, 2003). Moreover, scientists redefined soil quality in terms of the multiple functions that soils deliver within an ecosystem (Doran & Parkin, 1994; Larson & Pierce, 1994; Warkentin, 1995) and are essential to the sustainable development of society (Bouma, 2014; Schulte et al., 2015), including: (a) water purification and regulation, (b) soil biodiversity and habitat provision, (c) nutrient cycling, and (d) climate regulation, including carbon sequestration, in addition to (e) agricultural or primary productivity. As soil functions are bundles of soil processes (Kibblewhite, Ritz, & Swift, 2008) that arise from the interactions between physical, chemical and biological components of the soil (Vogel et al., 2018), the current scientific challenge is to develop models that can capture and assess soil multifunctionality from the field to continental scale. Such models would not only advance our knowledge on soil functioning, but also provide crucial information to land managers and other decision makers about how to utilize soils to provide the functions to which they are best suited (Haygarth & Ritz, 2009; Pulleman et al., 2012).

So far, several approaches for evaluating soil functions have been developed and discussed. Some tools operate on the field scale and take site-specific user preferences into consideration during indicator selection (Andrews, Karlen, & Cambardella, 2004; Rutgers et al., 2012). Another approach is to distinguish between static and dynamic soil indicators to quantify the potential and current state of soils in supplying different functions (Vogel et al., 2019), whereas other studies suggest solely focusing on static or slowly changing soil properties using digital soil mapping techniques (Greiner et al., 2018). Vrebos et al. (2020) published one of the few studies that modelled relationships between soil functions at the European scale using Bayesian networks, yet their assessment mainly relied on proxy indicators.

Indeed, many models only consider static soil properties, proxy indicators or even a limited number of soil functions, excluding data on current soil management. Greiner, Keller, Grêt-Regamey, and Papritz (2017) concluded that most models estimating the delivery of ecosystem services only included one or two soil functions, not truly representing the multifunctionality of the soil system. In this paper, we will follow the functional land management framework (Schulte et al., 2014) and use the Soil Navigator Decision Support System (DSS) (Debeljak et al., 2019), which can give a dynamic estimate of soil multifunctionality at a given site based on soil, climate and management attributes using multi-criteria decision modelling. The soil attributes that are used as input data for the Soil Navigator DSS are commonly used in existing monitoring schemes in Europe (van Leeuwen et al., 2017). The Soil Navigator DSS also requires collection of management attributes for all sites; this is not currently applied in large-scale monitoring, but this pilot study tests whether this approach would offer the opportunity to monitor soil functions at the European scale for the first time.

In addition to the value of soil function models to national and European soil monitoring programmes, modelling soil functions can also help us understand and predict the effect of management and environmental change on soil multifunctionality (Vogel et al., 2019). Although soils are expected to supply all functions, some soils are better at delivering certain functions than others (Coyle, Creamer, Schulte, O'Sullivan, & Jordan, 2016; Schulte et al., 2015). These differences can be explained by synergies or trade-offs between soil functions, which are likely to vary across soils as a consequence of soil properties, management and climatic conditions and can change over time in response to policy interventions and environmental change (Bennett, Peterson, & Gordon, 2009; Dade, Mitchell, McAlpine, & Rhodes, 2019). Understanding these complex relationships between soil functions from the field to European scale is crucial to developing sound policy interventions and recommending appropriate land use and soil management practices to optimize soil multifunctionality in different climatic regions of the EU (Valujeva, O'Sullivan, Gutzler, Fealy, & Schulte, 2016; Vrebos et al., 2017). Although studies have shown that agricultural land use can increase and decrease the delivery of different ecosystem services simultaneously, they also highlight the need to assess these relationships across space and time (Power, 2010). Despite the numerous long-term field experiments in Europe, lack of collaboration among existing sites, differences in experimental setups and under-representation of certain regions limit our understanding of spatial variations in ecosystem trade-offs and synergies across Europe (Howe, Suich, Vira, & Mace, 2014; Sandén et al., 2018). Limited knowledge on how the relationships between soil functions vary by land-use type and climatic zones makes it challenging to determine which soil functions to prioritize on different farms to meet the societal demands for food security and environmental sustainability, enhancing the likelihood that policy interventions and management actions may have unwanted effects on soil multifunctionality.

To address these challenges, this study explored the current status of soil multifunctionality in Europe and the interactions between soil functions across five climatic zones and two land-use types (arable and grassland). Soil, climate and management data were collected throughout Europe and assessed using the Soil Navigator DSS to demonstrate for the first time that monitoring multifunctionally at the European scale is possible. We hypothesized that soil multifunctionality can be optimized but cannot be maximized. In other words, we expected to find few sites supplying all five soil functions at the maximum level due to trade-offs between the functions. Through optimization we would propose that a soil delivers all five soil functions at a level to support soil quality standards while only supplying a few functions at maximum capacity to respond to the societal demands for food production and environmental sustainability. As management actions and environmental conditions influence the relationship between ecosystem services (Dade et al., 2019), we also hypothesized that synergies and trade-offs between soil functions vary by land use and climatic zone.

2 | METHODS

2.1 | Site selection, sampling methodology and field measurements

We selected 94 sites distributed across 13 European counties covering two land-use types (arable and grassland) and five climatic zones (see Figure S1 for map of site locations). Climatic zones included Alpine south, Atlantic, Continental, Mediterranean north and Pannonian (Table 1) and were defined based on the Environmental Stratification of Europe in Environmental Zones by Metzger, Bunce, Jongman, Mücher, and Watkins (2005). Their stratification system classifies environmental zones, which we refer to as climatic zones, using climate data, elevation data and data identifying differences in day length and buffering from the ocean (Jongman et al., 2006). All arable sites followed a cereal rotation with either lifted crops (beets, potatoes, carrots), mown oil crops (sunflower, rape) or legumes. For site selection, we used the help and expertise of local

TABLE 1 Replication of sites within each climatic zone by land-use type and soil diagnostic

Climatic zone	Number of grassland sites	Number of arable sites	Number of sites with calcic diagnostic	Number of sites with argic diagnostic
Alpine south	7	6	7	6
Atlantic	10	10	10	10
Continental	9	11	10	10
Mediterranean north	8	11	6	12
Pannonian	12	10	12	10

partners. Beside climatic zone and land use, we attempted to include two soil diagnostics (calcic and argic) in our site sampling design. However, due to the lack of detailed pedological maps across Europe, prediction of field locations where the specific diagnostics may occur proved to be poor, when sites were visited and classified, resulting in a large diversity of both mineral and organic soils with a wide range of soil characteristics (e.g., pH_{water} = 5.8–9.2, clay content = <1–69% and organic carbon = 4.5–211.8 g kg^{-1} dry soil) across all the sites. We would therefore advise not including diagnostics in European monitoring systems until soil maps are improved. Therefore, all soil function analyses were based on climatic region and land use only.

All sites were sampled within an 8-week period from mid-April until mid-June 2018. The data collection at the sites was divided between two sampling teams starting in the south of Europe and heading north. At each location, one designated field was sampled on a 10 × 10 m representative area that was situated at least 3 m away from the edges of the field and was selected in collaboration with the farmer, if present. A grid with 100 1 × 1 m grid squares was placed on top of this area and three squares were randomly chosen for soil sample collection. Soil samples from these three squares were taken at two depths (0–25 and 25–50-cm depth) and combined into a composite sample for each depth. Soil samples for biological analysis were taking from 0–15-cm depth. Bulk density was measured on the three separate squares by means of the core method (ISO 11272: 1998) at a depth of 12.5 cm and 32.5 cm to represent both sampling depths using a ring with diameter and height of 5 cm to get a measure of field variation. Aboveground biomass, infiltration capacity and earthworm samples (20 × 20 × 20 cm blocks) were measured from three separate randomly selected 1 × 1 m grids. All soil biological samples were taken and immediately stored in a cooler at 4°C for transportation to the laboratory.

To determine earthworm abundance, soil samples were gently broken apart into small pieces (∼1 cm) in the field. Whole worms or heads were counted. For species identification, earthworms were conserved in 70% ethanol solution. Earthworm samples were only taken where samples could be transported by car to the laboratory for species identification or local experts were present. To measure infiltration capacity, plant residues were removed from the soil surface and a metal core (diameter = 7.6 cm, height = 12.5 cm) was inserted into the soil up to 7.6-cm depth. Then water was added to the core, up to 1 in. (2.54 cm), amounting to 107 mL, and time needed for infiltration into the soil was recorded.

In addition to taking these soil samples and measurements on location, farmers were interviewed about their management practices related to fertilisers, crops, livestock, irrigation, artificial drainage, liming, and pest and disease control by means of a questionnaire (Creamer et al., 2019). Interviews took about 30–40 min. If the farmers were unsure about an answer, they consulted their own records to ensure the accuracy of their responses. Climate data were provided by the Agri4Cast team of the Joint Research Centre in Ispra (Italy). This dataset contains daily meteorological data coming from weather stations and interpolated on a 25 × 25 km grid. Data are available on a daily basis from 1975 to the last calendar year completed, covering the EU Member States, neighbouring European countries and the Mediterranean countries (see https://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx). Climate indicators for the five function models were computed from the raw data by INFOSOL and the AGROCLIM service unit of the Institut National de la Recherche Agronomique (INRA).

2.2 | Laboratory analysis

Upon arrival at the laboratory, soil biological samples were stored at 4°C and analysed within 6 weeks of sampling. Other soil samples were oven-dried at 40°C for 72 hr and sieved to <2 mm before awaiting further chemical or physical analysis. For some analyses (e.g., total carbon and nitrogen), soils were sieved to <0.25 mm. As described in Creamer et al. (2019), the following soil attributes were measured: soil texture (pipette method, ISO 11277:2009), bulk density (Massey et al., 2014), soil moisture, pH in water and calcium chloride (van Reeuwijk, 1992), cation-exchange capacity using a modified protocol of the Gillman method according to NEN 5738 (Gillman, 1979), total and organic soil carbon and nitrogen using the Dumas method with a CHN1110 Element Analyser (CE instruments, Milan, Italy), Mehlich-3 phosphorus (Mehlich, 1984), earthworm abundance, earthworm richness using the identification key by Bouché (1972) and Sims and Gerard (1985), nematode abundance, and nematode richness using the Oostenbrink method (Bongers, 1994; Oostenbrink, 1960). The Rosetta model (Schaap, Leij, & van Genuchten, 2001) was used to estimate soil drainage class based on the measurement of soil organic matter, bulk density and particle-size distribution.

2.3 | Decision modelling

The Soil Navigator DSS (Debeljak et al., 2019) was used to estimate the performance of the five soil functions at the 94 sites based on soil, management (interview) and climate data collected from the field as described in the previous section. The Soil Navigator DSS consists of seven modules linked with information and data flows, where the module of five multi-criteria decision models presents the central part. This module simultaneously assesses the performance of the five soil functions using five decision models (Sandén et al., 2019; Schröder et al., 2016; Trajanov et al., 2019; Van de Broek et al., 2019; van Leeuwen et al., 2019; Wall et al., 2020). Each model follows the hierarchical structure of a decision tree, where each input attribute (related to soil characteristics, climate variables and management practices) is evaluated utilizing a decision table and allocated a class of low, moderate or high (see Figure 1 for the model structure of the climate regulation model as an example of how the five function models were organized to assess functionality based on their different input attributes). Management attributes are an integral part of soil function assessment in addition to soil and climate attributes. At each branch of the decision tree, expert-based qualitative integration decision rules are applied to the classes of the lower-level attributes. Moving up the decision tree, the integrated (higher-level) attributes and finally the soil function itself at the top of the decision model are evaluated. The integrated attributes can provide valuable information about how different aspects of a given soil function are performing. The integrated attributes directly linked to the uppermost soil function score for each model are: (a) soil and environmental conditions, cropping system and management practices for Primary Productivity, (b) storage, drainage and runoff for Water Regulation and Purification, (c) nutrients, biology, structure and hydrology for Biodiversity and Habitat Provision, (d) mineralization, nutrient recovery and harvest index for Nutrient Cycling, and (e) carbon sequestration, nitrous oxide emissions and methane emissions for Climate Regulation. These five qualitative soil function models were structured, calibrated and validated using information obtained by expert knowledge and data mining (Debeljak et al., 2019). The Soil Navigator DSS can be freely accessed at www.soilnavigator.eu. It is important to note that the five soil function models show overlap in terms of data input. For example, soil organic matter or soil organic carbon is used as data input into four of the five function models. This creates interconnections between soil functions as observed in the field. Yet, the threshold values and decision rules used to assess the input attributes are unique for each function model.

2.4 | Statistics and data analysis

Data management, data visualization and statistical analyses were performed in R (R Core Team, 2019). To assess soil multifunctionality across sites, we counted the number of individual soil functions that scored low or high at each site. For determining the confidence intervals of these observed score counts, we used the bootstrapping method (Hilborn & Mangel, 1997) conditional on the observed probabilities of occurrence in our dataset. We took 100 random draws using the observed probabilities, using a multinomial distribution, and used the interval between 2.5 and 97.5% quantiles as the confidence interval. Synergies and trade-offs were defined as positive or negative relationships between soil functions, which were tested across land-use types and climatic zones using two different approaches. As a first method, we constructed a network of soil function score co-occurrences and used the `cooccur` package to perform a probabilistic co-occurrence analysis (Griffith, Veech, & Marsh, 2016; Veech, 2013). This method is most commonly used for testing species co-occurrences across sites and calculates the probability that two species (in our case two function scores, such as high biodiversity and high climate regulation) co-occur less frequently (*P(lt)*) or more frequently (*P(gt)*) than the observed count of co-occurrence if the two were randomly distributed among sites (expected). These probabilities can be interpreted as *p*-values ($\alpha = .05$). The method also determines the effect size indicating the difference between expected and observed counts (number of sites) of co-occurrence, which can be standardized between −1 and 1 by dividing by the

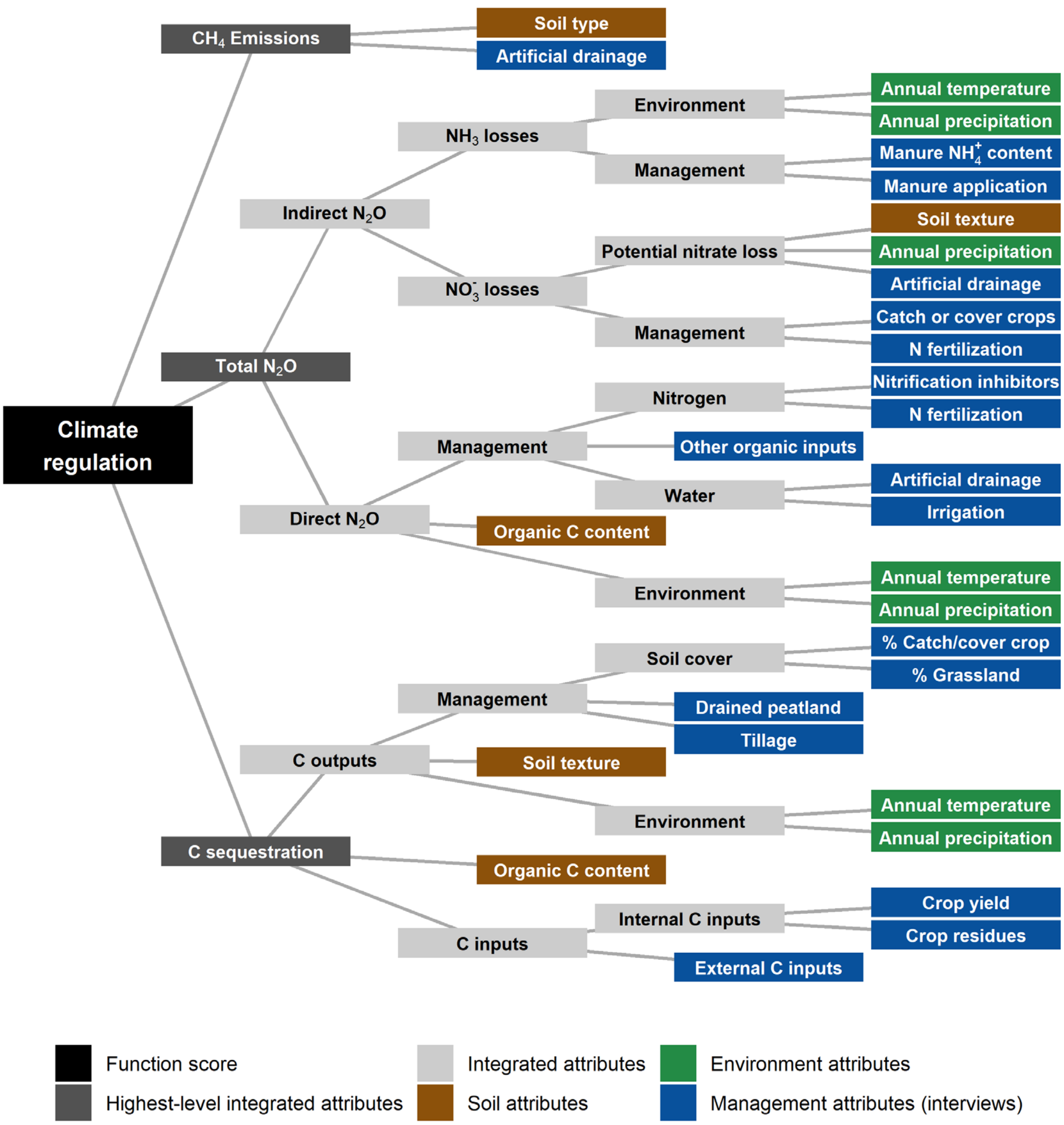

FIGURE 1 Model structure of the climate regulation model (modified from Van de Broek et al., 2019) as an example of how the five function models are organized to assess functionality based on their different input attributes: soil (brown), environment or climate (green) and management (blue). Scores of input attributes are determined based on set thresholds. Scores of integrated attributes (grey and dark grey) are determined by decision rules and scores of lower-level attributes. Function score (black) is determined by decision rules and scores of highest-level integrated attributes [Color figure can be viewed at wileyonlinelibrary.com]

number of sites included in the analysis (Griffith et al., 2016). Using this co-occurrence method, synergies are detected when alike scores (e.g., high climate regulation and high biodiversity) co-occur more frequently than expected or when opposite scores (e.g., high climate regulation and low biodiversity) co-occur less frequently than expected, whereas trade-offs are defined as alike scores co-occurring less frequently than expected or as opposite scores co-occurring more frequently than expected. As a second approach, we used the `Hmisc` package (Harrel, 2018) to calculate Spearman rank correlations where soil functions were treated as ordinal variables. Using this method, synergies and trade-offs are defined as positive and negative correlations, respectively. Correlations between soil functions were only calculated on sites with the same land use and climatic zone. The soil, management and climate data used in this study will become available through LANDMARKH2020 Dataverse (Portail Data INRA, 2020) but data access is restricted until January 2021.

3 | RESULTS

3.1 | Soil function scores

From the assessments of the soils at the 94 sites across Europe, we found that 33 out of the 94 sites had no “low”

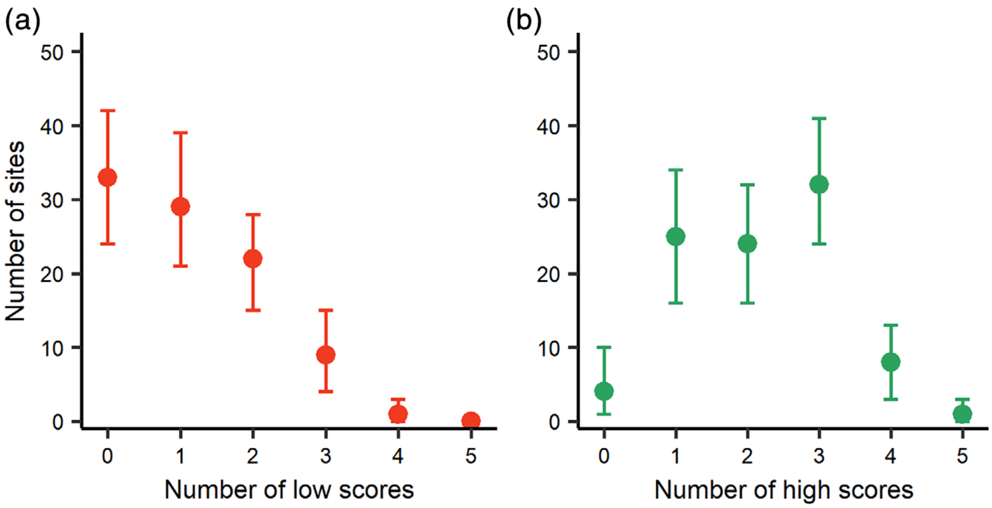

FIGURE 2 Frequency of sites with the number of (a) low and (b) high function scores out of a total of five per site (n_{tot} = 94). Bars indicate the confidence intervals of the observed counts determined by bootstrapping [Color figure can be viewed at wileyonlinelibrary.com]

scores for any of the five soil functions (Figure 2a), indicating that these soils delivered all five soil functions at either moderate or high capacity. In addition, none of the sites had low performance for all five soil functions. Likewise, very few sites received five high soil function scores (Figure 2b). In fact, only one grassland site supplied all five soil functions at high capacity. Most sites (81 out of the 94 sites) scored high for one (25 sites), two (24 sites) or three soil functions (32 sites). Grasslands generally delivered a greater number of soil functions at high capacity compared to arable sites (Figure S2). When assessed by climatic zone, most sites in the Pannonian and Mediterranean north climatic zones received one or zero low soil function scores, supplying all other functions at either moderate or high capacity (Figure S3).

Differences in performance of the individual functions were clearly visible (Figure 3). Although primary productivity and water regulation were most commonly supplied at high capacity, nutrient cycling performed at moderate capacity in most sites. Both the biodiversity and climate regulation soil functions had approximately an equal number of sites with a low, moderate and high score. We also found different patterns in soil function scoring between land-use types and climatic zones (Figure S4). Most strikingly, arable sites in the Alpine South performed very poorly in terms of climate regulation, whereas grassland sites supplied the climate regulation function mostly at high capacity.

3.2 | Co-occurrences of soil function scores

Soil function scores showed different patterns of co-occurrence in grassland and arable sites (Figure 3, Table 2). For the grassland sites, we found a significant positive co-occurrence between high scores of the climate regulation and biodiversity functions, suggesting a synergistic relationship. However, within the arable sites, both synergies and trade-offs were evident. Four significant co-occurrences were detected between the water regulation and climate regulation function scores, suggesting a synergistic relationship between the two functions. Potential trade-offs between soil functions were also detected, as high scores for climate regulation co-occurred more frequently than expected with low scores for primary productivity. In addition, soils delivering primary productivity at low capacity co-occurred less frequently than expected with moderate scores for biodiversity.

When performing the co-occurrence analyses within each climatic zone, we found an additional layer of variation (Table S1). Interestingly, these co-occurrence patterns were opposite for different climatic zones. For example, high scores for climate regulation and biodiversity co-occurred more frequently than expected in grassland sites of the Pannonian climatic zone, whereas the opposite pattern (high biodiversity and low climate regulation) was detected in arable sites of the Atlantic.

3.3 | Correlations between soil functions

Consistent with the co-occurrence analysis, positive and negative correlations between soil functions varied by land use and climatic zone (Table 3). The most prominent example was the relationship between climate regulation and biodiversity in the different land-use systems and climatic zones (Figure 4). Although these two soil functions showed a synergistic relationship in both grassland and arable sites in the Pannonian climatic zone, we found a trade-off between climate regulation and biodiversity in the arable sites of the Atlantic. For all other

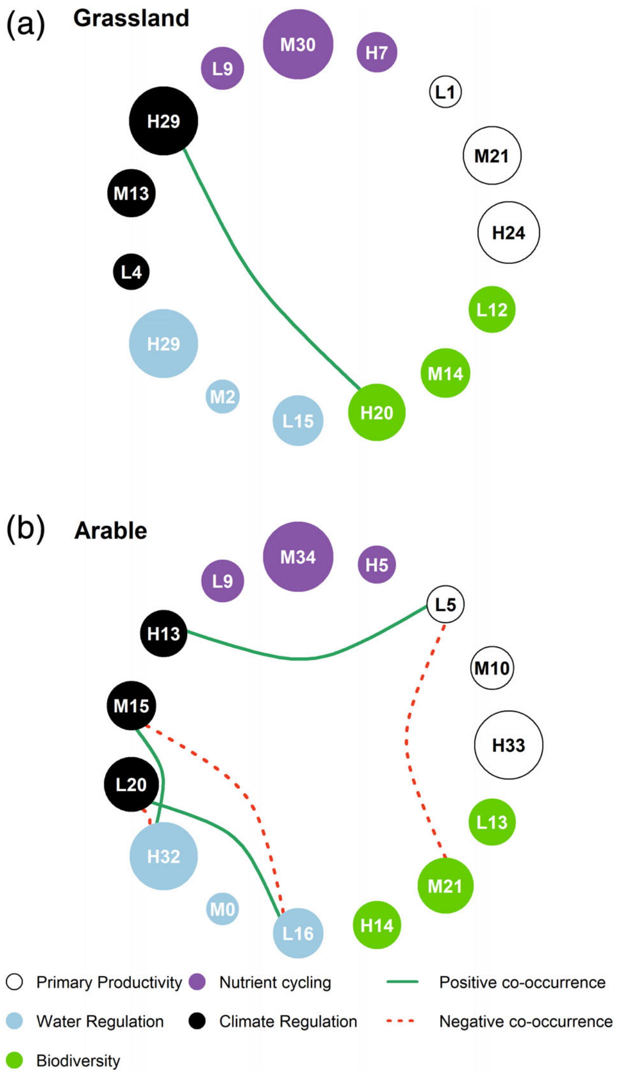

FIGURE 3 Network of significant positive and negative co-occurrences of soil function scores in (a) grassland ($n_{tot} = 46$) and (b) arable sites ($n_{tot} = 48$). Soil functions are indicated by colour: primary productivity (white), biodiversity (green), water regulation (blue), climate regulation (black) and nutrient cycling (purple). The low, moderate and high score of each soil function is indicated by L, M and H, respectively. The size of the node and value inside the node refer to the number of sites with that particular function score. Positive co-occurrences ($P(gt) < 0.05$) are indicated by a green solid line and negative co-occurrences ($P(lt) < 0.05$) are indicated by a red dotted line. See Table 2 for a summary of the associated probabilistic co-occurrence analyses [Color figure can be viewed at wileyonlinelibrary.com]

climatic zone and land use combinations, we did not find a significant relationship between these two soil functions. In addition, we detected significant synergies between (a) water regulation and biodiversity, (b) nutrient cycling and climate regulation, (c) nutrient cycling and water regulation, and (d) water regulation and climate regulation. The primary productivity function did not positively correlate with any of the other soil functions but did show significant trade-offs with climate regulation in the arable sites of the Continental climatic zone and with water regulation in grassland sites of the Mediterranean north.

4 | DISCUSSION

4.1 | Monitoring and optimizing soil multifunctionality

This research demonstrates that monitoring soil functions at the European scale is possible and provides preliminary targets for optimization. Soil multifunctionality provides a framework for soil quality assessment (Karlen et al., 1997) and moves beyond the assessment of soil properties. By aggregating soil, management and climate attributes, the Soil Navigator DSS does not only capture the capacity of a soil to supply several soil functions but also weighs the interactions between the soil processes, defining the synergies and trade-offs that ultimately determine soil quality. Although our findings show that agricultural land can deliver multiple functions at high capacity, only one grassland site achieved high scores on all five functions simultaneously (Figure 2). These results support a functional land management approach to soil quality assessment, which advocates for the optimization of soil multifunctionality considering societal demands rather than an attempt to maximize all five soil functions simultaneously (Schulte et al., 2015). Therefore, we recommend aiming for three high function scores and avoiding low scores as two realistic targets for managing soil multifunctionality at the farm scale.

As these conclusions are based on the evaluation of soil multifunctionality at different sites across Europe, one can raise the question of whether these current scores could be optimized beyond three high scores. This may indeed be possible for grasslands, of which more than half (24 sites) already supplied three or more functions at high capacity (Figure S2). Yet, in the case of arable land, this is more challenging to achieve due to trade-offs between soil functions (Tables 2 and 3) and contrasting effects of alternative management strategies on soil quality indicators (Sandén et al., 2018). Power (2010) also specifically points to trade-offs between ecosystem services that could result from agricultural practices and advocates that management should focus on both optimizing ecosystem services and reducing trade-offs.

It is important to note that the sample size of this study (94 sites) was rather small, when considering a pan-European assessment. This study was a preliminary study to assess whether it is possible to monitor soil

TABLE 2 Summary table of probabilistic co-occurrence analysis of soil function scores in grassland and arable sites

Land use	SF1	SF2	Site count with SF1	Site count with SF2	Observed count of sites with co-occurrence	Expected count of sites with co-occurrence	*P(lt)*	*P(gt)*	Standardized effect size
Grassland	BD (high)	CR (high)	20	29	17	12.6		0.007	0.096
Arable	PP (low)	BD (moderate)	5	21	0	2.2	0.047		−0.046
Arable	PP (low)	CR (high)	5	13	4	1.4		0.015	0.054
Arable	WR (high)	CR (low)	32	20	7	13.3	<0.001		−0.131
Arable	WR (high)	CR (moderate)	32	15	14	10		0.007	0.083
Arable	WR (low)	CR (low)	16	20	13	6.7		<0.001	0.131
Arable	WR (low)	CR (moderate)	16	15	1	5	0.007		−0.083

Note: Number of sites with individual function scores and co-occurrences are shown. *P(lt)* and *P(gt)* can be interpreted as *p*-values as they show the probability of finding a lower (lt) or higher (gt) frequency of co-occurrences than observed if all function scores were distributed randomly. Only significant co-occurrences between climate regulation (CR), biodiversity (BD), water regulation (WR) and primary productivity (PP) are shown. SF1 is soil function 1 and SF2 is soil function 2.

TABLE 3 Significant relationships between soil functions climate regulation (CR), biodiversity (BD), nutrient cycling (NC), water regulation (WR) and primary productivity (PP) across land uses and climatic zones assessed with Spearman correlations

Land use	Climatic zone	Soil functions		r_s	*p*-value
Grassland	Mediterranean north	PP	WR	−0.77	**.02**
Grassland	Mediterranean north	WR	BD	−0.75	**.03**
Grassland	Pannonian	NC	CR	0.61	**.04**
Grassland	Pannonian	CR	BD	0.69	**.01**
Arable	Alpine south	NC	WR	1.00	**<.001**
Arable	Atlantic	CR	BD	−0.72	**.02**
Arable	Continental	PP	CR	−0.72	**.01**
Arable	Continental	WR	CR	0.81	**<.001**
Arable	Pannonian	CR	BD	0.69	**.03**

Note: For a full list of soil functions tested, see Table S2 in Supporting Information.

functions across Europe covering a wide range of soil properties, climates and land-use types and has been successful in achieving this. However, additional assessment is needed to further validate the initial positive and negative relationships observed with this dataset, when considering land use and climatic zones separately, for developing management recommendations tailored towards specific regions. To scale up, we see great potential in the LUCAS-Soil survey (Orgiazzi, Ballabio, Panagos, Jones, & Fernández-Ugalde, 2018; Tóth, Jones, & Montanarella, 2013), which samples and analyses topsoil at approximately 20,000 sites across the EU. The LUCAS-Soil survey already monitors most of the soil properties needed to estimate soil multifunctionality using the Soil Navigator DSS. Crucial soil attributes that are still missing for monitoring soil functions at the European scale include soil bulk density and soil biological data (van Leeuwen et al., 2017). In addition, management attributes would also need to be collected; an example of the questionnaire developed in the LANDMARK project can be found in Creamer et al. (2019).

4.2 | Synergies and trade-offs

Land-use types and climatic zones showed marked differences in the synergies and trade-offs that occurred between soil functions (Figure 3, Table 3), supporting the need for tailor-made approaches to sustainable land management dependent on local conditions. Previous publications indeed warn that soil functions may compete and interact over space and time (Blum, 1990, 2005). In terms of ecosystem service delivery, modelling efforts at the European and national level have also demonstrated the importance of considering spatial heterogeneity and climate as drivers of synergies and trade-offs between

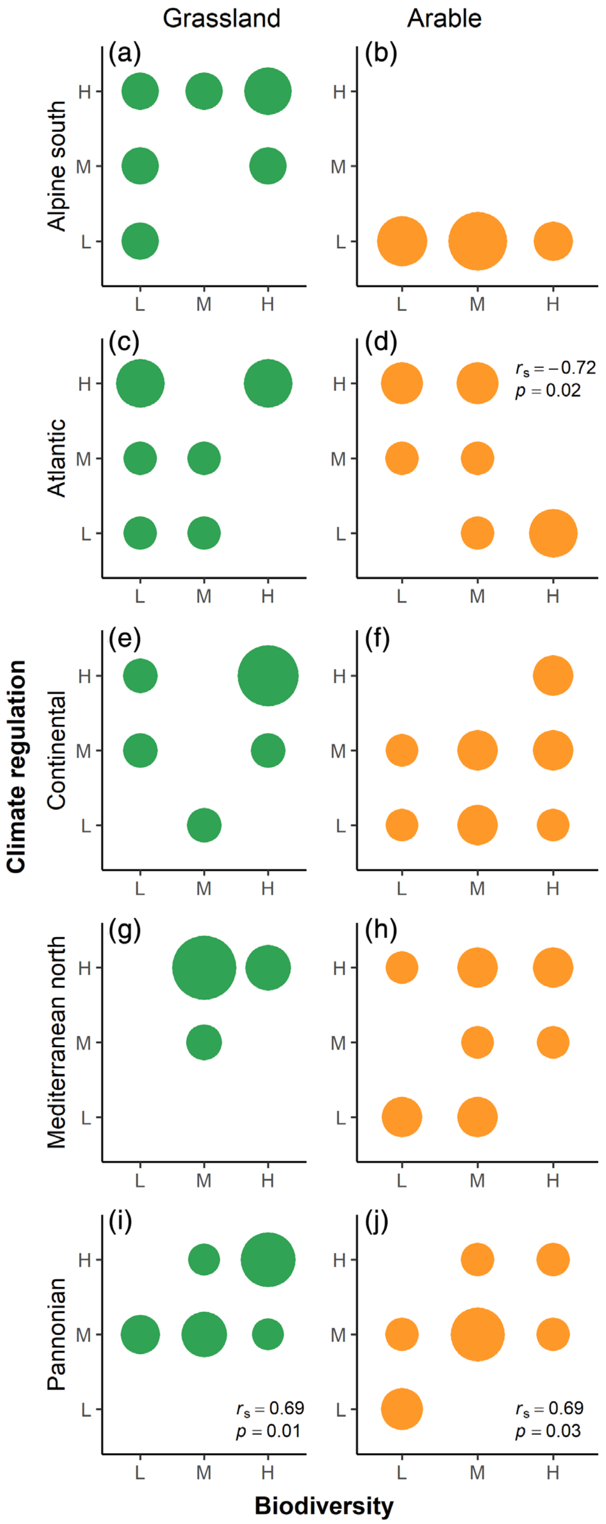

FIGURE 4 Relationship between climate regulation and biodiversity at grassland (n_{tot} = 46) and arable sites (n_{tot} = 48) in the Alpine south, Atlantic, Continental, Mediterranean north and Pannonian climatic zones. The number of sites per data point is indicated by the size of the bubble. Only coefficients and *p*-values of significant Spearman rank correlations are shown [Color figure can be viewed at wileyonlinelibrary.com]

agricultural production and regulation and maintenance services for achieving multifunctionality at the landscape level (Kirchner et al., 2015; Maes, Paracchini, Zulian, Dunbar, & Alkemade, 2012; Turner, Odgaard, Bøcher, Dalgaard, & Svenning, 2014).

Co-occurrence analyses (Figure 3) and Spearman correlations (Figure 4) both suggest a synergistic relationship between soil biodiversity and climate regulation, which can be explained by the crucial role of soil organic matter in both soil functions (Rutgers, Akkerhuis, & Bloem, 2010; Van de Broek et al., 2019; van Leeuwen et al., 2019). In fact, soil organic matter decline has been identified as one of the largest threats to soil biodiversity in Europe (Orgiazzi et al., 2016). The trade-off between biodiversity and climate regulation in arable sites of the Atlantic (10 sites) could be due to the combination of high fertilisation rates (data not shown) and relatively wet soils creating hydrological conditions that stimulate the denitrification process, resulting in increased nitrous oxide emissions (De Klein & Van Logtestijn, 1994; Dobbie & Smith, 2003). These contrasting relationships between soil biodiversity and climate regulation in different climatic zones and land uses demonstrate the complexity of interactions between soil functions that can be influenced by a variety of soil, management and climate factors depending on local conditions.

Primary productivity only showed trade-offs with two other soil functions: climate regulation and water regulation. Whether these trade-offs are a consequence of management or inherent soil and climate attributes warrants further investigation in order to determine to what extent these specific trade-offs can be minimized. As primary productivity is the economic foundation for farmers and associated sectors in rural areas (Turpin et al., 2017), considering trade-offs with primary productivity is particularly important in order to ensure farmers will be able to afford transitioning towards farming practices that enhance other soil functions demanded by society. Moreover, minimizing trade-offs with other soil functions may only be achievable when they are caused by land use or management, which are within the farmers' control. Brady, Hristov, Wilhelmsson, and Hedlund (2019) also point out that alternative soil management practices stimulating the delivery of soil-based ecosystem services other than food provision mostly benefit society rather than the farmers in the short term and that innovative governance strategies are needed to facilitate this transition.

Such a transition is currently being proposed under the new "conditionality" framework of the future CAP (European Commission, 2018), which supports improved soil quality and protection, and increased carbon sequestration through better land use and cover management. Farmers must comply with good agricultural and environmental conditions (GAECs), linked to their direct income support. Soil-specific GAECs include protection of peatlands and wetlands, crop rotation (replaces crop diversification), minimum land management under tillage to reduce soil degradation, and soil cover. Specifically, the impact of the CAP will be assessed through a set of impact indicators, several of which are soil dependent (e.g., soil organic carbon, soil erosion, pesticide use), or where soil has high relevance (e.g. biodiversity). As our research shows, monitoring soil multifunctionality across Europe is possible and could serve as an additional method for impact assessment of this framework, as well as help identify and avoid potential trade-offs.

4.3 | Imbalances in soil multifunctionality

For the realization of functional land management in Europe, the mosaic of local soil functionalities should sum up and respond to the societal demands for soil functions at a regional level (Schulte et al., 2015). Although societal demand can vary by function and member state (Schulte et al., 2019) and should be taken into consideration during optimization, our preliminary assessment shows a great imbalance in the delivery of soil functions at high capacity and suggests prioritizing policy interventions and management strategies that would support the enhancement of the nutrient cycling, biodiversity and climate regulation functions.

Techen and Helming (2017) identified future qualitative and quantitative agricultural management changes and analysed how they would affect soil multifunctionality in Germany. Their foresight analysis demonstrated that there is a lack of scientific knowledge about the effects of these practices on soil functions, especially with regards to the soil biodiversity and habitat provision function. In terms of future research, spatial arrangements of cropping systems, crop rotations, mechanical pressures and soil inputs have been highlighted as research categories that require special attention to enhance our understanding of interactions between management practices and soil functioning (Techen et al., 2020). Managing crop residues and the timing of fertiliser applications (inputs) could indeed support the nutrient cycling function (Schröder et al., 2018). When assessing the management attributes and scores for integrated attributes of the soil carbon sequestration and climate regulation model (Figure 1, data not shown), lowering nitrous oxide emissions and increasing soil carbon storage will be key. Although various recommendations have been put forward to increase soil carbon sequestration (Conant, Cerri, Osborne, & Paustian, 2017; Lal, 2008) and reduce greenhouse gas emissions (Davidson, 2009; Snyder, Bruulsema, Jensen, & Fixen, 2009; van Groenigen, Velthof, Oenema, van Groenigen, & Kessel, 2010), recent publications also underline a series of limitations and knowledge gaps that still need to be resolved (Chenu et al., 2019; Poulton, Johnston, Macdonald, White, & Powlson, 2018).

As the Soil Navigator DSS was developed to only require basic soil and climate attributes, scaling up the approach of this study to a greater number of sites and higher diversity of farms in different regions of the EU could be achieved quite easily and support the development of management recommendations to optimize soil multifunctionality. Collecting the essential management input attributes for the Soil Navigator DSS is essential to understand the dynamic behaviour of soil functions in relation to agricultural land management. One should also keep in mind that the Soil Navigator DSS is a qualitative model generating three output scores (low, moderate, high), which works well as a decision support and monitoring tool. However, if the goal is to unravel the underlying soil processes and interactions with environmental factors and farm management at a local scale, a more mechanistic model would be applicable. Yet, these models currently only exist for a single function or a few functions.

5 | CONCLUSION

This study marks the first step towards assessing and monitoring soil multifunctionality across Europe. Our findings show that soils can deliver multiple functions at high capacity but that local constraints and trade-offs between soil functions make it unrealistic to demand that soils should perform highly on each of the five soil functions assessed. Rather than a focus on maximizing all soil functions simultaneously, we argue that agri-environmental policies and management actions should aim for optimizing soil multifunctionality. Through optimization we suggest assessing and realising the unique potential of each soil to deliver soil functions based on current and future land use, climate and soil properties. In practice, this means identifying the soil functions that can be delivered at high capacity while avoiding trade-offs and low performance of the other soil functions. Our results indicate that managing soils to deliver three functions at high capacity is an achievable target. Although individual farms or even fields cannot be expected to deliver all soil functions at high capacity, these local functionalities should add up to meet societal demands at the national and European scale. Therefore, future research on managing the functionality of biodiversity and habitat provision, climate regulation and nutrient cycling should be prioritized as these functions were delivered less frequently at high capacity. With this preliminary assessment of soil multifunctionality at 94 sites covering a wide range of soil properties, we demonstrated that it is possible to monitor soil functions at the European level. An obvious next step is to scale up and perform this assessment at a higher number of sites covering a greater diversity of land-use types, management strategies and soil types, and covering all climatic zones in Europe at a higher resolution.

ACKNOWLEDGEMENTS

This project received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 635201. We thank Ekatharina Vasquez (Wageningen University), Lisa Castel (UniLaSalle campus Rouen), Aurélien Noraz (Conservatoire des Espaces Naturels Normandie Seine), Cedric Berger (Chamber of Agriculture, 45, France), Nicolas Saby (INFOSOL INRA), Teodor Rusa (University of Agricultural Sciences and Veterinary Medicine), Gilles Collinet (University of Liège), Else K. Bünemann (FiBL), Lisa Mølgaard Lehmann (University of Copenhagen), Helene Berthold (AGES), University of Parma, Research Centre Laimburg, Teagasc, Chamber of Agriculture Lower Saxony, and Szent István University for their help with site identification and field sampling, Patrick Bertuzzi and Nicolas Saby for processing climate and environmental data, Johan Six and Vladimir Kuzmanovski for their contributions to the Soil Navigator DSS, and Jaap Schröder and Aneta Trajanov for their contributions to the Soil Navigator DSS and feedback on the manuscript.

AUTHOR CONTRIBUTIONS

David Wall: Methodology; writing-review and editing. **Taru Sandén:** Methodology; writing-review and editing. **Arwyn Jones:** Writing-review and editing. **Rachel Creamer:** Conceptualization; funding acquisition; methodology; project administration; supervision; writing-review and editing. **Lia Hemerik:** Formal analysis; writing-review and editing. **Jeroen van Leeuwen:** Conceptualization; investigation; methodology; project administration. **Michiel Rutgers:** Methodology; writing-review and editing. **Henk Martens:** Investigation; writing-review and editing. **Marko Debeljak:** Methodology; writing-review and editing. **Marijn Van de Broek:** Methodology; writing-review and editing. **Iolanda Simo Josa:** Investigation; writing-review and editing. **Marie Jasmijn Zwetsloot:** Conceptualization; formal analysis; visualization; writing-original draft.

CONFLICT OF INTERESTS

The authors declare that they have no known conflicting interests that could have influenced the work reported in this manuscript.

DATA AVAILABILITY STATEMENT

The soil, management and climate data used in this study will become available through LANDMARKH2020 Dataverse (Portail Data INRA, 2020) but data access is restricted until January 2021.

ORCID

Marie J. Zwetsloot https://orcid.org/0000-0002-9392-213X
Rachel E. Creamer https://orcid.org/0000-0003-3617-1357

REFERENCES

Andrews, S. S., Karlen, D. L., & Cambardella, C. A. (2004). The soil management assessment framework. *Soil Science Society of America Journal*, *68*, 1945–1962.

Bennett, E. M., Peterson, G. D., & Gordon, L. J. (2009). Understanding relationships among multiple ecosystem services. *Ecology Letters*, *12*, 1394–1404.

Blum, W. E. H. (1990). The challenge of soil protection in Europe. *Environmental Conservation*, *17*, 72–74.

Blum, W. E. H. (2005). Functions of soil for society and the environment. *Reviews in Environmental Science and Bio/Technology*, *4*, 75–79.

Bongers, T. (1994). *De Nematoden van Nederland*. KNNV-bibliotheek uitgave 46. Pirola, Schoorl: The Netherlands.

Bouché, M. B. (1972). *Lombriciens de France: Écologie et systématique*. Paris, France: Institut National de la Recherche Agronomique.

Bouma, J. (2014). Soil science contributions towards sustainable development goals and their implementation: Linking soil functions with ecosystem services. *Journal of Plant Nutrition and Soil Science*, *177*, 111–120.

Brady, M. V., Hristov, J., Wilhelmsson, F., & Hedlund, K. (2019). Roadmap for valuing soil ecosystem services to inform multi-level decision-making in agriculture. *Sustainability*, *11*, 5285.

Bünemann, E. K., Bongiorno, G., Bai, Z., Creamer, R. E., De Deyn, G., de Goede, R., … Brussaard, L. (2018). Soil quality – A critical review. *Soil Biology and Biochemistry*, *120*, 105–125.

Chenu, C., Angers, D. A., Barré, P., Derrien, D., Arrouays, D., & Balesdent, J. (2019). Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil and Tillage Research*, *188*, 41–52.

Conant, R. T., Cerri, C. E. P., Osborne, B. B., & Paustian, K. (2017). Grassland management impacts on soil carbon stocks: A new synthesis. *Ecological Applications*, *27*, 662–668.

Coyle, C., Creamer, R. E., Schulte, R. P. O., O'Sullivan, L., & Jordan, P. (2016). A functional land management conceptual framework under soil drainage and land use scenarios. *Environmental Science & Policy*, *56*, 39–48.

Creamer, R., Zwetsloot, M., van Leeuwen, J., Martens, H., Brus, D., Simo Yosa, I., Hemerik, L., Micheli, E., Csorba, A., Jones, A. & Saby, N. 2019. *Monitoring schema for regional and European application, testing and assessment of indicators for five soil functions*. LANDMARK Report 5.2. Retrieved from www.landmark2020.eu

Dade, M. C., Mitchell, M. G. E., McAlpine, C. A., & Rhodes, J. R. (2019). Assessing ecosystem service trade-offs and synergies: The need for a more mechanistic approach. *Ambio*, *48*, 1116–1128.

Davidson, E. A. (2009). The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience*, *2*, 659–662.

De Klein, C. A. M., & Van Logtestijn, R. S. P. (1994). Denitrification in the top soil of managed grasslands in the Netherlands in relation to soil type and fertilizer level. *Plant and Soil*, *163*, 33–44.

Debeljak, M., Trajanov, A., Kuzmanovski, V., Schröder, J., Sandén, T., Spiegel, H., … Henriksen, C. B. (2019). A field-scale decision support system for assessment and management of soil functions. *Frontiers in Environmental Science*, *7*, 115. https://doi.org/10.3389/fenvs.2019.00115

Dobbie, K. E., & Smith, K. A. (2003). Nitrous oxide emission factors for agricultural soils in Great Britain: The impact of soil water-filled pore space and other controlling variables. *Global Change Biology*, *9*, 204–218.

Doran, J. W., & Parkin, T. B. (1994). Defining and assessing soil quality. J. W. Doran, D. C. Coleman, D. F. Bezdicek, & B. A. Stewart. In *Defining soil quality for a sustainable environment* (pp. 3–21). Madison, WI: SSSA.

European Commission. 2014. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A policy framework for climate and energy in the period from 2020 to 2030. Retrieved from http://register.consilium.europa.eu/doc/srv?l=EN&f=ST%205644%202014%20REV%201

European Commission. 2018. EU Budget: the Common Agricultural Policy beyond 2020. Retrieved from https://europa.eu/rapid/press-release_MEMO-18-3974_en.htm

European Commission. 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. The European Green Deal. Brussels. Retrieved from https://ec.europa.eu/info/sites/info/files/european-green-deal-communication_en.pdf

European Economic Community. 1991. Council directive of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:01991L0676-20081211&from=EN

Gerland, P., Raftery, A. E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., … Wilmoth, J. (2014). World population stabilization unlikely this century. *Science*, *346*, 234–237.

Gillman, G. P. (1979). A proposed method for the measurement of exchange properties of highly weathered soils. *Soil Research*, *17*, 129–139.

Greiner, L., Nussbaum, M., Papritz, A., Fraefel, M., Zimmermann, S., Schwab, P., … Keller, A. (2018). Assessment of soil multi-functionality to support the sustainable use of soil resources on the Swiss Plateau. *Geoderma Regional*, *14*, e00181.

Greiner, L., Keller, A., Grêt-Regamey, A., & Papritz, A. (2017). Soil function assessment: Review of methods for quantifying the contributions of soils to ecosystem services. *Land Use Policy*, *69*, 224–237.

Griffith, D. M., Veech, J. A., & Marsh, C. J. (2016). Cooccur: Probabilistic species co-occurrence analysis in R. *Journal of Statistical Software*, *69*, 1–17.

van Groenigen, J. W., Velthof, G. L., Oenema, O., van Groenigen, K. J., & Kessel, C. V. (2010). Towards an agronomic assessment of N_2O emissions: A case study for arable crops. *European Journal of Soil Science*, *61*, 903–913.

Harrel, F. 2018. Hmisc: Harrel Miscellaneous. R package version 4.1–1. Retrieved from https://CRAN.R-project.org/package=Hmisc

Haygarth, P. M., & Ritz, K. (2009). The future of soils and land use in the UK: Soil systems for the provision of land-based ecosystem services. *Land Use Policy*, *26*, S187–S197.

Hilborn, R., & Mangel, M. (1997). *The ecological detective: Confronting models with data*. Princeton, NJ: Princeton University Press.

Howe, C., Suich, H., Vira, B., & Mace, G. M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, *28*, 263–275.

ISO (International Organization for Standardization). (1998). *ISO 11272:1998. Soil quality - determination of dry bulk density*. Geneva: International Organization for Standardization.

ISO (International Organization for Standardization). (2009). *ISO 11277:2009. Soil quality - determination of particle size distribution in mineral soil material - Method by sieving and sedimentation*. Geneva: International Organization for Standardization.

Jongman, R. H. G., Bunce, R. G. H., Metzger, M. J., Mücher, C. A., Howard, D. C., & Mateus, V. L. (2006). Objectives and applications of a statistical environmental stratification of Europe. *Landscape Ecology*, *21*, 409–419.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F., & Schuman, G. E. (1997). Soil quality: A concept, definition, and framework for evaluation (a guest editorial). *Soil Science Society of America Journal*, *61*, 4–10.

Karlen, D. L., Ditzler, C. A., & Andrews, S. S. (2003). Soil quality: Why and how? *Geoderma*, *114*, 145–156.

Kibblewhite, M. G., Ritz, K., & Swift, M. J. (2008). Soil health in agricultural systems. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*, 685–701.

Kirchner, M., Schmidt, J., Kindermann, G., Kulmer, V., Mitter, H., Prettenthaler, F., … Schmid, E. (2015). Ecosystem services and economic development in Austrian agricultural landscapes — The impact of policy and climate change scenarios on trade-offs and synergies. *Ecological Economics*, *109*, 161–174.

Klingebiel, A. A., & Montgomery, P. H. (1961). *Land-capability classification*. Washington D.C.: Soil Conservation Service, U.S. Department of Agriculture.

Lal, R. (2008). Carbon sequestration. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*, 815–830.

Lal, R. (2009). Soils and world food security. *Soil and Tillage Research*, *102*, 1–4.

Larson, W. E., & Pierce, F. J. (1994). The dynamics of soil quality as a measure of sustainable management. J. W. Doran D. C. Coleman D. F. Bezdicek & B. A. Stewart In *Defining soil quality for a sustainable environment* (pp. 37–51). Madison, WI: SSA.

van Leeuwen, J. P., Saby, N. P. A., Jones, A., Louwagie, G., Micheli, E., Rutgers, M., … Creamer, R. E. (2017). Gap assessment in current soil monitoring networks across Europe for measuring soil functions. *Environmental Research Letters*, *12*, 124007. https://doi.org/10.1088/1748-9326/aa9c5c

van Leeuwen, J. P., Creamer, R., Cluzeau, D., Debeljak, M., Gatti, F., Henriksen, C. B., … Rutgers, M. (2019). Modeling of soil functions for assessing soil quality: Soil biodiversity and habitat provisioning. *Frontiers in Environmental Science*, *7*, 113. https://doi.org/10.3389/fenvs.2019.00113

Maes, J., Paracchini, M. L., Zulian, G., Dunbar, M. B., & Alkemade, R. (2012). Synergies and trade-offs between ecosystem service supply, biodiversity, and habitat conservation status in Europe. *Biological Conservation*, *155*, 1–12.

Massey, P., O'Connor, C., Sills, P., Fenelon, A., Maloney-Finn, L., Reidy, B., & Creamer, R. (2014). *Irish Soil Information System: Laboratory Standard Operating Procedures (2007-S-CD-1-S1)*. EPA STRIVE Programme 2007–2013. Dublin, Ireland: Environmental Protection Agency.

Martel, Y. A., & Mackenzie, A. F. (1980). Long-term effects of cultivation and land use on soil quality in Quebec. *Canadian Journal of Soil Science*, *60*, 411–420.

Mausel, P. W. (1971). Soil quality in Illinois—An example of a soils geography resource analysis. *The Professional Geographer*, *23*, 127–136.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis*, *15*, 1409–1416.

Metzger, M. J., Bunce, R. G. H., Jongman, R. H. G., Mücher, C. A., & Watkins, J. W. (2005). A climatic stratification of the environment of Europe. *Global Ecology and Biogeography*, *14*, 549–563.

Oostenbrink, M. (1960). Estimating nematode populations by some selected methods. J. N. Sasser, & W. R. Jenkins. *Nematology*, 85–102). Chapel Hill, NC: The University of North Carolina Press.

Orgiazzi, A., Ballabio, C., Panagos, P., Jones, A., & Fernández-Ugalde, O. (2018). LUCAS soil, the largest expandable soil dataset for Europe: A review. *European Journal of Soil Science*, *69*, 140–153.

Orgiazzi, A., Panagos, P., Yigini, Y., Dunbar, M. B., Gardi, C., Montanarella, L., & Ballabio, C. (2016). A knowledge-based approach to estimating the magnitude and spatial patterns of potential threats to soil biodiversity. *Science of the Total Environment*, *545–546*, 11–20.

Portail Data INRA. 2020. LANDMARKH2020 Dataverse. Retrieved from https://data.inra.fr/dataverse/LandmarkH2020

Poulton, P., Johnston, J., Macdonald, A., White, R., & Powlson, D. (2018). Major limitations to achieving "4 per 1000" increases in soil organic carbon stock in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. *Global Change Biology*, *24*, 2563–2584.

Power, A. G. (2010). Ecosystem services and agriculture: Tradeoffs and synergies. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*, 2959–2971.

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G., & Rutgers, M. (2012). Soil biodiversity, biological indicators and soil ecosystem services—An overview of European approaches. *Current Opinion in Environmental Sustainability*, *4*, 529–538.

van Reeuwijk, L. P. (1992). *Procedures for soil analysis* (ISRIC Technical Paper). Wageningen: International Soil Reference and Information Centre.

R Core Team, 2019. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from https://www.R-project.org/

Rutgers, M., Akkerhuis, G.A.J.M.J. & Bloem, J. 2010. *Priority areas in the Soil Framework Directive: The significance of soil biodiversity and ecosystem services*. Bilthoven, the Netherlands: RIVM. Retrieved from https://research.wur.nl/en/publications/priority-areas-in-the-soil-framework-directive-the-significance-o

Rutgers, M., van Wijnen, H. J., Schouten, A. J., Mulder, C., Kuiten, A. M. P., Brussaard, L., & Breure, A. M. (2012). A method to assess ecosystem services developed from soil attributes with stakeholders and data of four arable farms. *Science of the Total Environment*, *415*, 39–48.

Sandén, T., Spiegel, H., Stüger, H.-P., Schlatter, N., Haslmayr, H.-P., Zavattaro, L., … Berge, H. t. (2018). European long-term field experiments: Knowledge gained about alternative management practices. *Soil Use and Management*, *34*, 167–176.

Sandén, T., Trajanov, A., Spiegel, H., Kuzmanovski, V., Saby, N. P. A., Picaud, C., … Debeljak, M. (2019). Development of an agricultural primary productivity decision support model: A case study in France. *Frontiers in Environmental Science*, *7*, 58. https://doi.org/10.3389/fenvs.2019.00058

Schaap, M. G., Leij, F. J., & van Genuchten, M. T. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal of Hydrology*, *251*, 163–176.

Schröder, J., Debeljak, M., Trajanov, A., Creamer, R.E., Delgado, A., Sandén, T., Spiegel, H. Schulte, R. and Wall, D. 2018. *Key indicators and management strategies for nutrient cycling*. LANDMARK Report 3.5. Retrieved from www.landmark2020.eu

Schröder, J. J., Schulte, R. P. O., Creamer, R. E., Delgado, A., van Leeuwen, J., Lehtinen, T., … Wall, D. P. (2016). The elusive role of soil quality in nutrient cycling: A review. *Soil Use and Management*, *32*, 476–486.

Schulte, R. P. O., Bampa, F., Bardy, M., Coyle, C., Creamer, R. E., Fealy, R., … Vrebos, D. (2015). Making the most of our land: Managing soil functions from local to continental scale. *Frontiers in Environmental Science*, *3*, 81. https://doi.org/10.3389/fenvs.2015.00081

Schulte, R. P. O., O'Sullivan, L., Vrebos, D., Bampa, F., Jones, A. & Staes, J. 2019. Demands on land: Mapping competing societal expectations for the functionality of agricultural soils in Europe. *Environmental Science & Policy*, *100*, 113–125.

Schulte, R. P. O., Creamer, R. E., Donnellan, T., Farrelly, N., Fealy, R., O'Donoghue, C., & O'hUallachain, D. (2014). Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science & Policy*, *38*, 45–58.

Sims, R., & Gerard, B. (1985). *Earthworms. Synopsis of British Fauna No. 31*. London, UK: Linnaean Society.

Snyder, C. S., Bruulsema, T. W., Jensen, T. L., & Fixen, P. E. (2009). Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture, Ecosystems & Environment*, *133*, 247–266.

Storie, R. E. (1933). *An index for rating the agricultural value of soils*Bulletin - University of California Agricultural Experiment Station, 556. Berkeley, CA: University of California.

Techen, A.-K., & Helming, K. (2017). Pressures on soil functions from soil management in Germany. A foresight review. *Agronomy for Sustainable Development*, *37*, 64. https://doi.org/10.1007/s13593-017-0473-3

Techen, A.-K., Helming, K., Brüggemann, N., Veldkamp, E., Reinhold-Hurek, B., Lorenz, M., … Vogel, H.-J. (2020). Soil research challenges in response to emerging agricultural soil management practices. In D. L. Sparks (Ed.), *Advances in agronomy* (pp. 179–240). Academic Press.

Tóth, G., Jones, A., & Montanarella, L. (2013). The LUCAS topsoil database and derived information on the regional variability of cropland topsoil properties in the European Union. *Environmental Monitoring and Assessment*, *185*, 7409–7425.

Trajanov, A., Schröder, J., Wall, D., Delgado, A., Schulte, R. & Debeljak, M. 2019. Assessing the nutrient cycling potential in agricultural soils using decision modelling. In: *Proceedings of the 15th International Symposium on Operational Research*. Ljubljana, Slovenia: Slovenian Society Informatika.

Turner, K. G., Odgaard, M. V., Bøcher, P. K., Dalgaard, T., & Svenning, J.-C. (2014). Bundling ecosystem services in Denmark: Trade-offs and synergies in a cultural landscape. *Landscape and Urban Planning*, *125*, 89–104.

Turpin, N., ten Berge, H., Grignani, C., Guzmán, G., Vanderlinden, K., Steinmann, H.-H., … Baumgarten, A. (2017). An assessment of policies affecting sustainable soil management in Europe and selected member states. *Land Use Policy*, *66*, 241–249.

UN. 2015. Paris Agreement. Retrieved from http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

Valujeva, K., O'Sullivan, L., Gutzler, C., Fealy, R., & Schulte, R. P. O. (2016). The challenge of managing soil functions at multiple scales: An optimisation study of the synergistic and antagonistic trade-offs between soil functions in Ireland. *Land Use Policy*, *58*, 335–347.

Van de Broek, M., Henriksen, C. B., Ghaley, B. B., Lugato, E., Kuzmanovski, V., Trajanov, A., … Six, J. (2019). Assessing the climate regulation potential of agricultural soils using a decision support tool adapted to stakeholders' needs and possibilities. *Frontiers in Environmental Science*, *7*, 131. https://doi.org/10.3389/fenvs.2019.00131

Veech, J. A. (2013). A probabilistic model for analysing species co-occurrence. *Global Ecology and Biogeography*, *22*, 252–260.

Verity, G. E., & Anderson, D. W. (1990). Soil erosion effects on soil quality and yield. *Canadian Journal of Soil Science*, *70*, 471–484.

Vogel, H.-J., Bartke, S., Daedlow, K., Helming, K., Kögel-Knabner, I., Lang, B., … Wollschläger, U. (2018). A systemic approach for modeling soil functions. *Soil*, *4*(1), 83–92.

Vogel, H.-J., Eberhardt, E., Franko, U., Lang, B., Ließ, M., Weller, U., … Wollschläger, U. (2019). Quantitative evaluation of soil functions: Potential and state. *Frontiers in Environmental Science*, *7*, 164.

Vrebos, D., Bampa, F., Creamer, R. E., Gardi, C., Ghaley, B. B., Jones, A., … Meire, P. (2017). The impact of policy instruments on soil multifunctionality in the European Union. *Sustainability*, *9*, 407.

Vrebos, D., Delgado, A., O'Sullivan, L., Creamer, R. E., Trajanov, A., Kuzmanovski, V., … Debeljak, M. (2020). Spatial evaluation and trade-off analysis of soil functions through Bayesian networks. *European Journal of Soil Science*.

Wall, D. P., Delgado, A., O'Sullivan, L., Creamer, R. E., Trajanov, A., Kuzmanovski, V., … Debeljak, M. (2020). A decision support model for assessing the water regulation and purification potential of agricultural soils across Europe. *Frontiers in Sustainable Food Systems*, *4*, 115.

Warkentin, B. P. (1995). The changing concept of soil quality. *Journal of Soil and Water Conservation*, *50*, 226–228.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Zwetsloot MJ, van Leeuwen J, Hemerik L, et al. Soil multifunctionality: Synergies and trade-offs across European climatic zones and land uses. *Eur J Soil Sci*. 2020;1–15. https://doi.org/10.1111/ejss.13051