



Short communication

Synergies and trade-offs between soil functions differ with land-use intensity

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ABSTRACT

The effect of soil management and the socio-economic system on soil function supply has been extensively studied. In contrast, the less explored question of how management intensity influences synergies and trade-offs between functions – i.e. the competition between function supplies – is addressed here. Using a large soil dataset spanning 28 European countries, we estimate five soil functions and calculate co-occurrence relationships, both positive and negative, between these functions. We then examine how competition between functions varies with management intensity, using a map of land system archetypes. Our findings reveal that competition between functions varies with land-use intensity but can also differ spatially within a single intensity class. For example, we identified instances of conflicting synergies and trade-offs within one class. We also found a strong positive relationship between primary productivity and nutrient cycling in more intensively managed land, whereas there was a trade-off between water regulation and primary productivity in less intensively managed lands. These findings support future regional land-use policies focused on soil health. However, we emphasize that beyond individual soil function supply, it is necessary to consider soil multifunctionality and understand how interactions between function supplies change in response to both environmental and socio-economic factors.

Soil functions, such as primary productivity, climate regulation, nutrient cycling, water regulation, and providing habitat for biodiversity, offer ecosystem services supporting human well-being (Blum, 2005). Although existing literature recognizes that these soil functions underpin assessments of soil quality, health, and security, there remains a notable absence of a definitive framework for quantifying them explicitly (Lechevallier et al., 2025). This challenge arises because soil functions are not directly measurable but emerge from the interactions between biotic and abiotic soil components, which in turn affect processes producing functions. Recently, various tools and methodologies have been devised to assess soil functions. Some of these tools employ empirical relationships that use indicators scored based on soil properties, while others depend on biogeochemical process-based models. These methods to evaluate soil function supply have been employed across diverse environmental settings, and from individual fields to regions and countries (Greiner et al., 2017).

The supply of soil functions varies spatially in response to environmental factors, soil type, land use, and soil management. These soil functions often show complex spatial interactions, where the enhancement of one function can lead to the degradation of another. Hereafter, we define a competing supply of soil functions in terms of synergy

and trade-off. Synergy occurs with a positive effect, where the increase in the supply of one function enhances another (i.e. co-occur with a positive correlation), whereas a trade-off occurs when the increase in one function reduces another (i.e. a negative correlation). For example, there is frequently competition between nutrient cycling and primary productivity (Schröder et al., 2016) whereas there may be a synergy between the climate regulation and the nutrient cycling. The synergies and trade-offs between functions also vary spatially (Zwetsloot et al., 2021). While there has been a lot of progress in soil function assessment, we still lack a comprehensive understanding of how the interaction in soil function supply varies spatially and the feedback they have with the environment and management.

Soil functions are what the soil does, independently of human interests, and are defined by soil characteristics derived from their formation and position in the landscape. Humans, however, can have a strong effect on soil function supply through management. The feedback loop and interaction of soil functions with the socio-economic system has been described extensively, for example, in Vogel et al. (2018): human activities on soil are mediated through management, and the feedback from soil to the socio-economic system occurs through soil functions.

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Here, we do not reiterate the numerous publications on the multiple effects of management on soil functions. Instead, we investigate the far less evident question of how management intensity affects the synergies and trade-offs between functions, i.e., the competition between function supplies.

We build on the recent work of Wadoux et al. (2026) which provided multi-attribute models for the large-scale assessment of five soil functions, along with a description and justification of the indicators used in for model development. The models were applied at the LUCAS soil samples (LUCAS, Jones et al., 2020) in the European Union. The LUCAS database contains data from approximately 22,000 (i.e. 0–30 cm) georeferenced topsoil samples spanning 28 European countries. The application of the multi-attribute soil function models to the LUCAS samples is described in Wadoux et al. (2025). In this manuscript, we report on the interaction between soil functions for the first time with a dataset at European scale. Our analysis is based on a static dataset and does not account for seasonal or interannual variability in soil functions. Consequently, the observed relationships and trade-offs should be interpreted as representative of long-term average conditions, although we acknowledge that disturbance of the relationships between functions can also occur with extreme climate events.

To understand how synergies and trade-offs between functions occurs, we calculated the co-occurrence of functions. Co-occurrence is defined as positive or negative directed relationship between functions. The co-occurrence was evaluated across land system archetypes, which represent different characteristic patterns and levels of management intensity (Levers et al., 2018) obtained from indicators of land cover and land-use intensity. The criteria included the proportion of cropland, pasture, forest, and semi-natural areas; land-use intensity indicators such as fertilizer application, livestock density, irrigation, and crop rotation; and relevant socioeconomic factors such as population density. These variables were integrated using self-organizing maps to cluster areas with similar characteristics, resulting in distinct, objectively defined land system prototypes that reflect gradients of management intensity. An example of land system archetype is high-intensity cropland.

We built a network of co-occurrence using the probabilistic model of Veech (2013) and commonly used in species co-occurrence analysis across sites. The probabilistic model give the probability (P) that two species co-occur at a frequency either lower ($P(lt)$) or higher ($P(gt)$) than the observed co-occurrence frequency. In our case, the two species are two functions within a land system archetype with a given level of provision (e.g. low provision of habitat for biodiversity and high provision of primary productivity). The probabilities are calculated analytically from a presence-absence table of the function by site and can be interpreted as p -values. Significant patterns of co-occurrence between functions can therefore be identified with the p -values, which test whether function 1 and 2 co-occur significantly less or more frequently than would be expected by chance. For more information on the equation of P , $P(lt)$ and $P(gt)$ we refer to Veech (2013). We further calculated the effect size by subtracting the expected count (i.e. number of sites) from the observed counts, which was standardized between -1 and 1 by dividing this difference by the number of sampling sites. In this co-occurrence analysis, synergies are found when two function scores occur more frequently than expected by chance, whereas trade-offs are when two function scores occur less than expected by chance. The probabilistic co-occurrence model was implemented in R using the `cooccur` package (Griffith et al., 2016) with the `cooccur` function whereas the standardized effect size was obtained with the `effect.sizes` function. To simplify the interpretation, we report on all co-occurrences in which the observed count of co-occurrence was greater than 10, and we disregarded co-occurrences related to medium soil function supply.

The analysis of co-occurrences across the land system archetypes reveals patterns related to nutrient cycling, habitat for biodiversity, and climate regulation in relation to intensity levels (i.e. land system

archetypes). In high-intensity systems, such as high-intensity cropland (Fig. 1a), there are strong positive co-occurrences between high levels of nutrient cycling, habitat for soil biodiversity, and primary productivity. However, notable trade-offs appear with negative co-occurrences between low climate regulation and high water regulation. As intensity decreases in systems like large-scale permanent cropland and high-intensity arable cropland, some positive relationships persist (e.g. high nutrient cycling with high primary productivity), but the interactions become more complex. For example, high nutrient cycling synergizes with low primary productivity and climate regulation. In medium- and low-intensity systems, such as medium-intensity arable cropland and low-intensity arable cropland, the pattern remains unchanged, but low nutrient cycling increasingly co-occurs negatively with climate regulation and productivity. Additionally, fallow farmland and livestock farming systems reflect similar trends, where high nutrient cycling supports productivity and biodiversity, while low levels create trade-offs with climate regulation and habitat quality. In low-intensity grassland areas, positive relationships with biodiversity also occur, but significant negative co-occurrences emerge between high nutrient cycling and low primary productivity. This may happen when microbial turnover sustains active nutrient dynamics, but slow-growing, stress-tolerant plant communities and other limiting factors constrain biomass production (Bardgett and Wardle, 2010). The high-intensity agricultural mosaic illustrates the positive effects of low nutrient cycling on biodiversity and habitat quality. Finally, the low-intensity mosaic (Fig. 1b) highlights mixed patterns where high nutrient cycling synergizes with high habitat for biodiversity and climate regulation. Overall, while we found that high nutrient cycling generally promotes productivity and biodiversity across intensity levels, trade-offs with climate regulation and water functions become increasingly crucial in lower-intensity systems.

While we observe that competition between soil functions varies with land-use intensity, we also find instances of conflicting synergies and trade-offs within a single intensity class. For example, in high-intensity arable cropland (see Supplementary Materials), both low and high levels of climate regulation are associated with low habitat for biodiversity. Similarly, in fallow farmland (see Supplementary Materials), a trade-off exists between low water regulation and low primary productivity, as well as between high water regulation and high primary productivity. These findings suggest that competition between functions is influenced by factors beyond land-use intensity and can vary spatially within a class. This is expected given the large-scale nature of the assessment, as land-use intensity classes vary across diverse geographical areas, soil types, and environmental zones in Europe. This is confirmed in Table 1: less than half synergies and trade-offs are occurring in various land system archetypes. For example, only three synergies occur in both high-intensity cropland and large-scale permanent cropland, out of ten co-occurrence present in the first land system archetype.

The findings on synergies and trade-offs align to some extent with earlier work on soil functions in Europe (e.g. Vrebos et al., 2021), although we observed a mixture of synergies and trade-offs across all environmental zones and functions. Soil functions inherently compete and interact across space and time (Blum, 2005; Evangelista et al., 2023). Consistent with many previous studies (e.g. O'Sullivan et al., 2015; Zhao et al., 2022), we identified a trade-off between primary productivity, water regulation, and climate regulation. This trade-off may be attributed to the intensive land use usually associated with high crop yields, which often leads to soil degradation (Panagos et al., 2016), reduced water infiltration, and loss of carbon. We also found a strong positive relationship between primary productivity and nutrient cycling, as well as another synergistic relationship between habitat for biodiversity and nutrient cycling. Although these synergies vary across management intensity areas, many previous studies confirm the connection between primary productivity in intensive systems and nutrient cycling, often at the expense of biodiversity (De Vries et al.,

Table 1

Change in synergies and trade-offs of soil functions between land system archetypes with varying intensity levels. The first number represents the number of synergy pairwise interactions occurring between the two land system archetypes, while the second number represents the number of trade-off pairwise interactions. The number in brackets indicates the total number of synergies and trade-offs in the original land system archetype.

		to										
		Large-scale permanent cropland	High-intensity arable cropland	Medium-intensity arable cropland	Low-intensity arable cropland	Fallow farmland	High-intensity livestock farming	Medium-intensity livestock farming	Low-intensity livestock farming	Low-intensity grassland area	High-intensity agricultural mosaic	Low-intensity mosaic
from	High-intensity cropland	3:0 (10)	4:1 (10)	5:2 (10)	6:1 (10)	4:0 (10)	2:0 (10)	4:0 (10)	4:1 (10)	4:1 (10)	2:0 (10)	3:0 (10)
	Large-scale permanent cropland	8:5 (13)	5:1 (13)	7:2 (13)	6:4 (13)	6:4 (13)	5:4 (13)	5:3 (13)	5:4 (13)	4:3 (13)	3:2 (13)	3:2 (13)
	High-intensity arable cropland	5:1 (26)	13:13 (26)	8:9 (26)	7:8 (26)	7:8 (26)	4:7 (26)	5:7 (26)	9:9 (26)	9:11 (26)	3:2 (26)	5:3 (26)
	Medium-intensity arable cropland	7:2 (26)	8:9 (26)	14:12 (26)	11:10 (26)	8:7 (26)	6:8 (26)	9:7 (26)	8:8 (26)	10:9 (26)	3:1 (26)	4:2 (26)
	Low-intensity arable cropland	6:4 (27)	7:8 (27)	11:10 (27)	13:14 (27)	7:8 (27)	4:8 (27)	8:7 (27)	8:8 (27)	8:9 (27)	2:2 (27)	4:3 (27)
	Fallow farmland	6:4 (20)	7:8 (20)	8:7 (20)	7:8 (20)	9:11 (20)	5:8 (20)	6:7 (20)	7:9 (20)	7:10 (20)	3:3 (20)	4:4 (20)
	High-intensity livestock farming	5:4 (17)	4:7 (17)	6:8 (17)	4:8 (17)	5:8 (17)	7:10 (17)	5:8 (17)	5:8 (17)	6:9 (17)	3:3 (17)	3:4 (17)
	Medium-intensity livestock farming	5:3 (20)	5:7 (20)	9:7 (20)	8:7 (20)	6:7 (20)	5:8 (20)	11:9 (20)	8:8 (20)	10:9 (20)	4:3 (20)	6:4 (20)
	Low-intensity livestock farming	5:4 (24)	9:9 (24)	8:8 (24)	8:8 (24)	7:9 (24)	5:8 (24)	8:8 (24)	12:12 (24)	11:10 (24)	3:3 (24)	6:4 (24)
	Low-intensity grassland area	4:3 (30)	9:11 (30)	10:9 (30)	8:9 (30)	7:10 (30)	6:9 (30)	10:9 (30)	11:10 (30)	15:15 (30)	4:3 (30)	6:4 (30)
	High-intensity agricultural mosaic	3:2 (10)	3:2 (10)	3:1 (10)	2:2 (10)	3:3 (10)	3:3 (10)	4:3 (10)	3:3 (10)	4:3 (10)	6:4 (10)	3:3 (10)
	Low-intensity mosaic	3:2 (10)	5:3 (10)	4:2 (10)	4:3 (10)	4:4 (10)	3:4 (10)	6:4 (10)	6:4 (10)	6:4 (10)	3:3 (10)	6:4 (10)

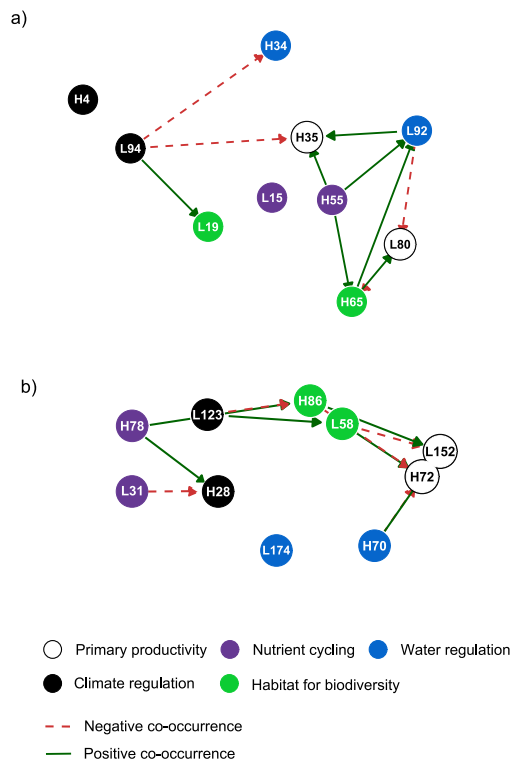


Fig. 1. Probabilistic co-occurrence network plot for two land system archetypes with two contrasted levels of management intensity; a high intensity with (a) the high-intensity cropland and a low intensity with (b) the low-intensity mosaic. Soil functions are indicated by the coloured bubble whereas the scores, either *Low* or *High* is indicated by the letters L and H, respectively, along with the number of sites where this function score occurs. Positive directed co-occurrence indicating synergies are shown with a solid green line while negative directed co-occurrence indicating trade-offs are shown with a dashed red line. See Supplementary Material the table of all significant co-occurrence for the other land system archetypes.

2013; Tsiafouli et al., 2015; Schröder et al., 2016). The synergy and trade-off analysis offers insights for future regional land use policy. For instance, identifying areas where unintended consequences of policy measures might exacerbate negative outcomes, such as biodiversity loss or compromised water regulation. However, further research is needed to better understand the additional underlying drivers of these synergies and trade-offs, and how they vary spatially and temporally.

While we found that land-use intensity affects the competition between soil functions, we did not find any threshold beyond which it suddenly reduces the number of synergies or antagonisms. Instead, most responses appear gradual. Context-specific tipping points may exist, such as when reductions in plant diversity trigger disproportionate declines in soil multifunctionality, although these are not generalizable across ecosystems (Felipe-Lucia et al., 2020). Similarly, while we quantified the presence and direction of trade-offs and synergies among soil functions, we did not assess their intensity. Within the probabilistic framework used in this paper, the intensity of pairwise relationships can be estimated by calculating a standardized deviation (z-score) of the observed co-occurrence relative to its expected value and variance. The strength of these relationships could help understand the extent to which management can reduce detrimental trade-offs or reinforce beneficial synergies. Investigating the intensity of these interactions would represent a valuable contribution for future research.

Although our analysis incorporates key environmental inputs, including broad-scale climate and soil characteristics, and uses land system prototypes to account for regional variation, spatial variation within the same management intensity level may still influence observed patterns. As a result, we cannot disentangle the effects of management intensity from other natural factors. This limitation could be addressed by explicitly including additional environmental covariates or employing mixed-effects modelling approaches to better separate management and environmental influences.

We conclude that synergies and trade-offs vary with the intensity of land use and that many co-occurrences are significant. This suggests a strong spatial interaction between functions (i.e. a competing supply), with part of this competition being driven by the socio-economic system (e.g. soil management, land use intensity). Therefore, in addition to looking at the supply of individual soil functions, which has been

the subject of many studies, it is important to assess the multifunctionality of soil and to understand how the interactions between the supply of functions vary spatially in response to environmental and socio-economic factors. These findings can help in the design of more differentiated agri-environmental policies, especially when it comes to achieving a balance between agricultural productivity and the maintenance of ecosystem services at different land use intensities. The spatial patterns observed across management intensity classes suggest that complementing European-scale analyses with more local assessments, for example at the scale of the soil districts (Wadoux et al., 2024), could help reveal potential heterogeneity within these classes that our large-scale approach could not explicitly capture. Our study further emphasizes the importance of considering soil as a multifunctional system in which trade-offs are not necessarily undesirable outcomes, but expressions of complex ecological interactions influenced by human activities. This systems perspective allows land managers to better understand the interconnectedness of soil processes and make decisions that promote long-term soil health and sustainability. The use of probabilistic co-occurrence modelling also represents a methodological advance in soil function research, as it enables the identification of consistent patterns of interaction across different landscapes and management regimes. In the face of increasing land-use pressures, integrating soil multifunctionality into a broader concept of sustainability will be crucial to support resilient agroecosystems and achieve goals related to climate regulation, water quality and biodiversity conservation.

CRediT authorship contribution statement

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

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at <https://doi.org/10.1016/j.agee.2025.110112>.

Data availability

The authors do not have permission to share data.

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