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Conventional and organic farms with more intensive management have lower soil functionality

Sophie Q. van Rijssel[1]†‡, Guusje J. Koorneef[2,3]†§, G. F. (Ciska) Veen[1], Mirjam M. Pulleman[3,4], Ron G. M. de Goede[3], Rob N. J. Comans[2,5], Wim H. van der Putten[1,6], Kyle Mason-Jones[1,7]*

Organic farming is often considered to be more sustainable than conventional farming. However, both farming systems comprise highly variable management practices. In this study, we show that in organic and conventional arable fields, the multifunctionality of soils decreases with increasing agricultural management intensity. Soil organic carbon content and bacterial biomass, respectively, were the strongest abiotic and biotic predictors of soil multifunctionality. Greater soil multifunctionality was associated with less-frequent inversion tillage and higher frequency of grass-legume cover cropping, and organic farming did not outperform conventional farming. Our results suggest that reducing management intensity will enhance soil multifunctionality in both conventional and organic farming. This implies that, in contexts where high-yielding, high-intensity agriculture prevails, the paradigm of sustainable intensification should be replaced by "productive deintensification."

Soils perform numerous ecological functions that underpin human and ecosystem health. In agricultural soils, maximized crop yield may come at the expense of soil functions, including water retention (*1*), making agriculture more sensitive to drought, or of less-efficient nutrient cycling, resulting in nutrient loss and pollution of water bodies (*2*). Intensive agricultural management can also reduce soil organic carbon (SOC) content and soil biodiversity (*3*, *4*), both strong determinants of soil functionality (*5*, *6*). Thus, increased crop yield may come at the cost of multiple functions (multifunctionality) and thus compromise soil health (*7*, *8*). The multifunctionality concept integrates soil functionality trade-offs and synergies that may otherwise be overlooked. With global soils facing multiple forms of degradation (*9*), there is a pressing need to enhance soil multifunctionality in order to produce food sustainably.

One widespread approach to improving soil health is organic farming, in which natural fertilizers and pest control are applied in place of synthetic inputs (*10*). Indeed, organic farming systems are reported to outperform conventional farming systems in numerous soil functions (*10*) and in multifunctionality overall (*11*). However, it is unclear whether functional differences are inherent to organic versus conventional farming or whether they actually originate from a combination of individual management practices that could be applied in either farming system (*12*, *13*). It is also important to understand whether agricultural management affects functions directly, or indirectly by altering the quantity or quality of SOC (*6*) or the composition of soil biological communities (*14*). Understanding the interplay between management practices, SOC, biota, and soil multifunctionality is crucial for establishing effective management targets and appropriate indicators of agricultural sustainability.

Experiments have shown how particular management practices affect soil functions; for example, it has been found that crop diversification can enhance pest control and nutrient cycling, reducing greenhouse gas emissions (*15*), and that pesticide application can affect soil enzyme activities (*16*). Comparison of multiple soil functions between sites is facilitated by aggregating the individual functions into a composite multifunctionality score (*8*, *17*). This strategy has shown that soil multifunctionality can, for example, be promoted by organic management and reduced tillage (*11*), manure application (*18*), and crop residue return (*19*).

Agricultural management is a multidimensional combination of practices, making comparisons between real farm systems challenging but nevertheless necessary for decision-making by consumers and policy-makers. The binary characterization of conventional versus organic farming has attained widespread public recognition and establishment within regulatory frameworks, despite comprising a range of different management practices (*20*). An alternative simplification is to aggregate management practices into a composite management intensity score (*13*, *21*), analogous to scoring multifunctionality. Applicable across both conventional and organic agriculture, this approach has the advantage that variability in practices is better reflected.

The aim of the present study is to examine how conventional versus organic farming, and agricultural management intensity, influence soil multifunctionality. We also determine whether these relationships can be explained by differences in the characteristics of SOC and soil microbiota. We use the term "conventional agriculture" as an analytical comparator in the sense of Sumberg & Giller (*22*), to denote farms whose practices are not organic nor self-identified as "alternative" agricultural practices, such as conservation or regenerative agriculture (*23*, *24*). Conventional farming represents the mainstream agricultural practices of the Netherlands, where our study was conducted. Organic practices exclude synthetic fertilizers and pesticides and are certified by "*Stichting Keur Alternatief voortgebrachte Landbouwproducten*" (SKAL) (*25*). We hypothesize that (i) organic agriculture outperforms conventional agriculture in terms of soil multifunctionality but that (ii) increasing agricultural management intensity is negatively related to soil multifunctionality in both organic and conventional farming. Furthermore, we postulate that these relationships are mediated by changes in soil biology and SOC, and we therefore hypothesize that (iii) soil biological and (iv) SOC characteristics significantly explain variation in multifunctionality by reflecting management practices.

Assessment of management intensity and soil multifunctionality

Our analysis is based on soils sampled across the Netherlands from 53 organic and conventional arable fields on two dominant mineral soil types (*26*–*29*). The sandy soils are classified as Anthrosols and clay soils as calcareous Fluvisols (*30*), with the sand or clay distinction accounting for the largest variation in pedogenic properties and therefore adopted as shorthand descriptors (fig. S1 and table S1). Sampled fields had comparable monocot crops (winter or spring wheat, barley, spelt or winter rye, or grass-legume mixtures as a representative cover crop). The organic fields varied in age from 4 to 69 years of organic management, with recently converted fields (0 to 3 years) excluded. The multifunctionality analysis integrated soil function indicators for nutrient cycling, decomposition, soil structure provision, pathogen control, and water regulation into a single multifunctionality score (materials and methods and table S2). Each indicator was scaled to the mean value for the respective soil type. Transformed indicator values were then averaged to obtain the aggregated multifunctionality score for each field (materials and methods) (*17*, *31*). We applied multiple approaches to characterize SOC and soil biota (Table 1 and table S3) and also examined whether

[1]Department of Terrestrial Ecology, Netherlands Institute for Ecology (NIOO-KNAW), Wageningen, Netherlands. [2]Soil Chemistry Group, Wageningen University & Research, Wageningen, Netherlands. [3]Soil Biology Group, Wageningen University & Research, Wageningen, Netherlands. [4]International Center for Tropical Agriculture (CIAT), Cali, Colombia. [5]TNO, Geological Survey of the Netherlands, Utrecht, Netherlands. [6]Laboratory of Nematology, Wageningen University & Research, Wageningen, Netherlands. [7]Soil Microbial Interactions, Department of Geoscience, University of Tübingen, Tübingen, Germany.
***Corresponding author. Email: k.masonjones@nioo.knaw.nl**
†These authors contributed equally to this work.
‡Present address: Soil Geography and Landscape Group, Wageningen University & Research, Wageningen, Netherlands.
§Present address: Department of Terrestrial Ecology, Netherlands Institute for Ecology (NIOO-KNAW), Wageningen, Netherlands.

Table 1. Overview of soil organic carbon (SOC) quality parameters considered in the analysis.

Abbreviation	Description	Unit	Type
Total SOC	Total soil organic carbon	g C kg^{-1} soil	Size of SOC
POXC	Permanganate-oxidizable organic carbon	g C kg^{-1} soil	Size of SOC fraction
POXC:SOC	Permanganate oxidizable organic carbon, expressed as proportion relative to total SOC content	g C g^{-1} C	Proportion of SOC fraction
POMC	SOC present as particulate organic matter (POM) (>50 μm), expressed in g C kg^{-1} soil or as proportion relative to total SOC content (g C g^{-1} C)	g C kg^{-1} soil	Size of SOC fraction
POMC:SOC		g C g^{-1} C	Proportion of SOC fraction
PyroC:SOC	Total pyrolyzable SOC, expressed as proportion relative to total SOC content (g C g^{-1} C)	g C kg^{-1} soil	Proportion of SOC fraction
MAOMC	SOC present as mineral-associated organic matter (MAOM) (<50 μm), expressed in g C kg^{-1} soil or as proportion relative to total SOC content (g C g^{-1} C)	g C kg^{-1} soil	Size of SOC fraction
MAOMC:SOC		g C g^{-1} C	Proportion of SOC fraction
StableC:SOC	Centennially persistent SOC, expressed as proportion relative to total SOC content (g C g^{-1} C)	g C kg^{-1} soil	Proportion of SOC fraction
Bulk_CN	The organic carbon-to-total-nitrogen ratio (C:N) of the bulk soil	g C g^{-1} N	Element ratio
POMC:N	The carbon-to-nitrogen ratio (C:N) of the fraction of coarse organic matter (>50 μm), that mainly consists of POM	g C g^{-1} N	Element ratio
MAOMC:N	The carbon-to-nitrogen ratio (C:N) of the fraction of fine organic matter (<50 μm), that mainly consists of MAOM	g C g^{-1} N	Element ratio
OI	Oxygen index, a proxy for the oxygen:carbon ratio of soil organic matter	mg O_2 g^{-1} C	Element ratio
T50pyr_CH	The temperature at which 50% of the carbon has converted to volatile hydrocarbon (i.e., CH) effluents during pyrolysis.	°C	Thermal stability
T50pyr_CO2	The temperature at which 50% of the carbon has converted to CO_2 during pyrolysis	°C	Thermal stability
T50ox_CO2	The temperature at which 50% of the carbon has converted to CO_2 during oxidation	°C	Thermal stability

multifunctionality relates to plant productivity using the normalized difference vegetation index (NDVI) from a previous study (*32*).

Various management practices have been previously used as management intensity indicators, including external inputs (*13*, *33*–*35*), organic residue removals (*13*, *33*), mechanical soil tillage (*4*, *33*–*35*), and narrow crop rotations (*4*, *35*). We adopted a definition of management intensity as the extent to which cropping practices alter soil processes (*34*). We used farm interviews during the sampling campaign to collect management data regarding organic matter inputs (external inputs per hectare and retention of crop residues), soil tillage (depth and frequency), and crop rotation (diversity, root and tuber crop frequency, and cover cropping) and aggregated these into a single management intensity score (materials and methods and table S4). Management practices can vary strongly and systematically by soil type, so the same approach to scaling and aggregation was applied here to each soil type separately, as for soil function indicators.

Soil multifunctionality is reduced under higher management intensity

Organic fields overall had lower management intensity scores than conventional fields [Fig. 1A; analysis of variance (ANOVA): $F_{1,49}$ = 14.2, P < 0.001]. However, our results do not support the hypothesis that organic fields outperform conventional fields in terms of multifunctionality because this relationship was absent overall and when considering clay or sand fields separately (Fig. 1B; ANOVA P_{ConOrg} > 0.3). Nevertheless, there was a significant negative relationship between management intensity and multifunctionality when considering all fields together (Fig. 1C; Spearman ρ = −0.30, P = 0.028). The relationship between management intensity and multifunctionality remained significant for organic fields alone (P = 0.033) but not for conventional fields (P = 0.31) (fig. S2). Given the consistent trend in both farming systems (fig. S2; ρ_{Org} = −0.43, ρ_{Con} = −0.17), the statistical significance in the combined analysis evidently benefited from the statistical power of the larger dataset with both management systems together. Growing season NDVI of the study fields (*32*) was not correlated to soil multifunctionality (Spearman ρ = 0.23, P = 0.095). Therefore, there was neither evidence of a synergy nor a trade-off between soil multifunctionality and plant productivity.

We further analyzed the multifunctionality scores while disaggregating management intensity into its seven different component practices: crop diversity, crop intensity, percentage grass-legume in the rotation, external organic matter inputs (e.g., compost, manure), tillage depth, time since the last inversion tillage, and crop residue removal (Fig. 2; fig. S9 shows the corresponding analysis of management intensity related to individual functions). Time since the last tillage significantly increased the multifunctionality score—which remained significant when disaggregating the fields by conventional and organic management—and was marginally significant in clay soils alone (table S5). The percentage of a mixed grass-legume cover crop in the rotation also had a significant effect on multifunctionality (Fig. 2C), which was driven especially by its effect in sandy soils (table S5). External organic matter inputs, tillage depth, crop diversity, and other factors were not significantly related to multifunctionality on their own, but sensitivity analysis indicated that crop diversity, crop residue removal, and tillage depth also contributed to the strength of the observed relation (table S6).

Soil organic matter, not soil microbiota, strongly predicts multifunctionality

Although C sequestration is a soil function, we excluded biological and SOC parameters from our multifunctionality scores. By considering these parameters separately, we were able to test their hypothesized relationships to other aspects of multifunctionality. Soil multifunctionality was significantly correlated with 8 out of 16 SOC parameters, with the strongest relationship to total SOC content (Fig. 3; Spearman ρ = 0.63, P_{adj} < 0.001). SOC quality parameters representing the size of different SOC pools were all strongly positively correlated with multifunctionality [Fig. 3; permanganate-oxidizable C (POXC), particulate organic matter C (POMC), and mineral-associated organic matter C (MAOMC)]. However, these SOC parameters were also strongly correlated to total SOC content (fig. S5). Total SOC C:N ratio and thermal stability parameters did not show any relationships to multifunctionality. Consistent but weaker trends were observed when clay and sandy soils were analyzed separately (fig. S6), whereas relationships between SOC parameters and multifunctionality

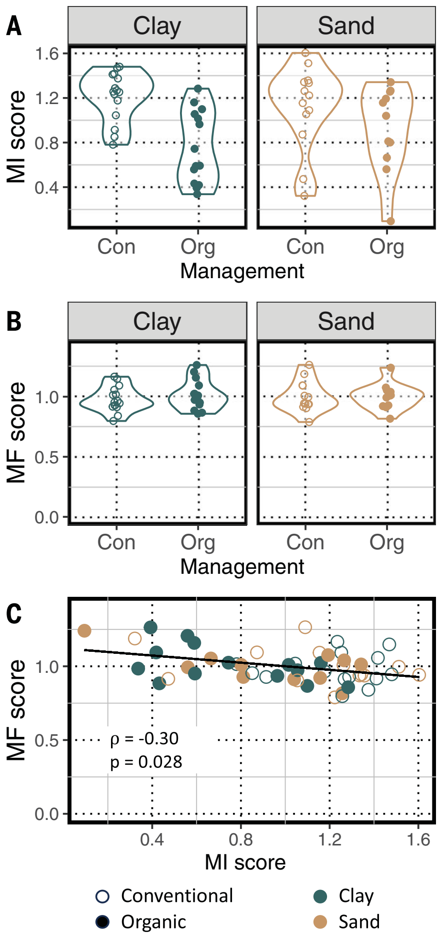

Fig. 1. Relationships between farming system, management intensity (MI), and soil multifunctionality (MF) across 53 farms in the Netherlands, on sandy and clay soils. (**A**) Organic management is less intensive than conventional management (ANOVA: $F_{1,49}$ = 14.2, P < 0.001) with no effect of or interaction with soil type. (**B**) The farming system does not, however, predict soil multifunctionality (ANOVA: not significant for farming system, soil type, and interactions). (**C**) Management intensity is negatively related to soil multifunctionality across both organic and conventional management systems (Spearman correlation illustrated with linear regression).

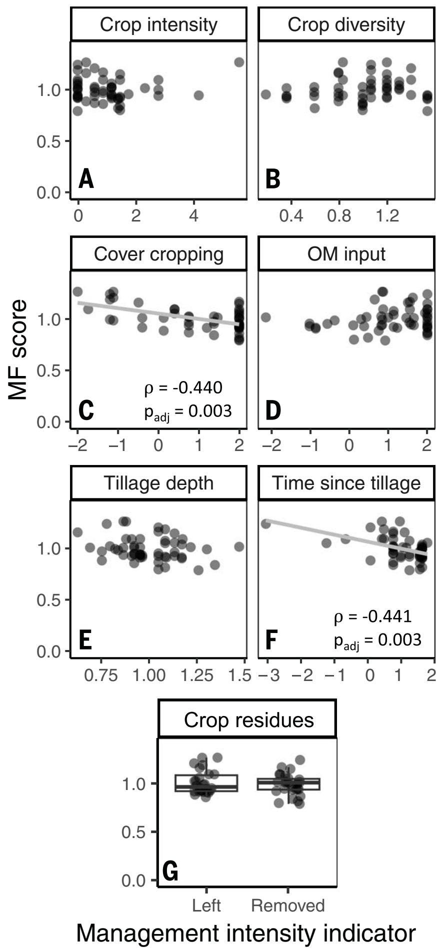

Fig. 2. Relationships between individual management intensity indicators and soil multifunctionality. (**A**) Crop intensity, determined as the frequency of root and bulb crops in the rotation. (**B**) Crop diversity in the rotation. (**C**) Grass-legume cover cropping (inverted indicator so that less cover cropping corresponds to higher intensity). (**D**) External organic matter inputs (inverted indicator). (**E**) Tillage depth. (**F**) Time since last tillage (inverted indicator). (**G**) Crop residue removal. Intensity indicators are scaled to the mean of the respective soil type.

were generally insensitive to multifunctionality indicator composition (tables S7 and S8). Including SOC content as a soil function would have made the negative relationship between management intensity and multifunctionality somewhat stronger (Spearman ρ = −0.34, P = 0.014).

Soil multifunctionality did not show any correlation with biological soil parameters (fungal biomass; nematode abundance; and the composition, richness, and diversity of microbial or nematode communities; Fig. 4 and fig. S3), except for a positive relationship with bacterial biomass (Fig. 4; ρ = 0.42, P_{adj} = 0.031), which was driven by sandy soils (fig. S3; clay: ρ = 0.16, P_{adj} = 0.73, sand: ρ = 0.77, P_{adj} < 0.001). Bacterial biomass may have appeared as a significant factor owing to its positive relationship with total SOC (fig. S4; ρ = 0.38, P = 0.005). Total SOC content therefore emerged as the strongest predictor of soil multifunctionality from the wide range of biological and SOC indicators considered in our study.

Total SOC content also showed a marginally significant relationship to management intensity overall (Spearman: ρ = −0.31, P_{adj} = 0.051), as well as a direct relationship to time since tillage (fig. S7; Spearman: ρ = −0.44, P_{adj} = 0.008) and cover cropping (Spearman: ρ = −0.39, P_{adj} = 0.011). Higher management intensity was also reflected in a decline in the absolute and relative pool size of POMC (fig. S8; P_{adj} = 0.005 and 0.019, respectively) and was positively correlated with one of two indicators of pyrolytic stability (fig. S8; T50pyr_CO2, P_{adj} = 0.019). Of these, POMC pools corresponded to higher multifunctionality (Fig. 3) and were strongly correlated to total SOC content (fig. S5). Direct effects of management were therefore strongly reflected in SOC parameters, which in turn appears to influence multifunctionality.

The composition of aggregated indicators for management intensity and multifunctionality is crucial in such analyses. A sensitivity analysis examined the effect of omitting individual functions or management indicators. In most cases, the relationship between management intensity and multifunctionality was conserved with at least marginal significance (Spearman: ρ = −0.24 to −0.37; P = 0.006 to 0.088). However, two parameters (percentage grass-legume cover in the rotation, and time elapsed since the previous tillage) were essential to the identified trend, and the removal of either resulted in the loss of the significant relationship (table S6). By contrast, exclusion of external organic matter input greatly enhanced the strength and significance of the relationship between management intensity and soil multifunctionality (Spearman ρ = −0.37, P = 0.006). This finding was confirmed by repeating the sensitivity analysis without considering external organic matter inputs: The significance of the relationship was then robust to the removal of other functions or management intensity indicators (Spearman ρ = −0.29 to −0.42; P = 0.001 to 0.029) except for cover cropping (ρ = −0.24, P = 0.083).

Discussion

Our aggregated metric of management intensity was a better predictor of soil multifunctionality than the organic/conventional dichotomy, suggesting that reductions in management intensity can potentially improve soil functionality in both farming systems. However, there was a difference between the two systems, because organic farming had a lower average management intensity score than conventional farming, as well as a wider variation of management intensities (coefficient of variation of 0.42 and 0.26 for organic and conventional, respectively). The wide range of organic management intensities may explain why organic systems together did not have significantly higher multifunctionality overall. This variability may also explain why the relationship between management intensity and multifunctionality remained significant for organic

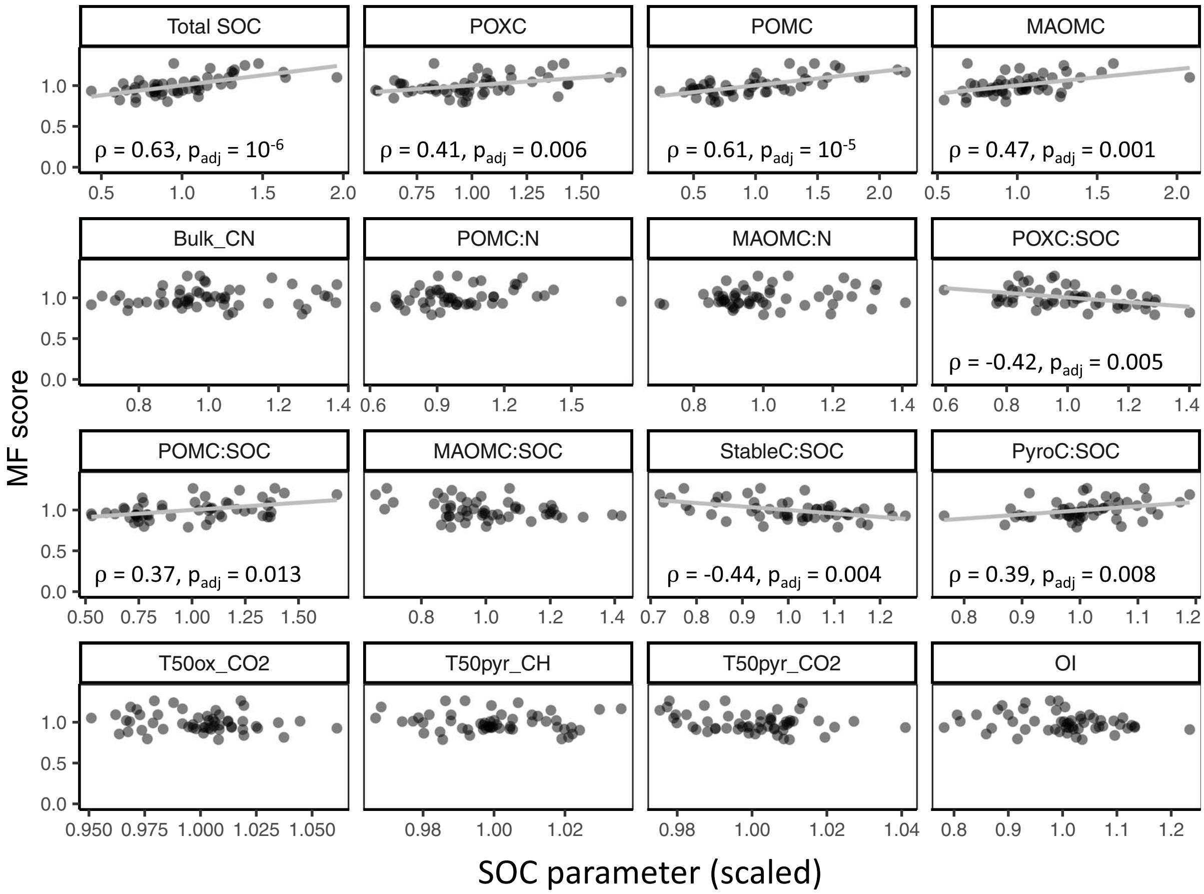

Fig. 3. Relationships between soil organic carbon parameters and soil multifunctionality (MF score). Soil organic matter parameters (Table 1) are scaled to the mean of the respective soil type, consistent with the scaling applied to the multifunctionality indicators. Total SOC: Total soil organic carbon in the bulk soil; POXC: pool size of permanganate-oxidizable C; POMC: pool size of particular organic matter C; MAOMC: pool size of mineral-associated organic matter C; Bulk_CN: C:N ratio of bulk soil; POMC:N: C:N ratio of POM; MAOMC:N: C:N ratio of MAOM; POXC:SOC, POMC:SOC, and MAOMC:SOC, respectively: POXC, POMC, and MAOMC as proportions of total SOC; StableC:SOC: centennially persistent SOC predicted from RockEval measurements as proportion of total SOC; PyroC:SOC: pyrolyzable SOC as proportion of total SOC; T50ox_CO2: temperature for 50% conversion of SOC to CO_2 during oxidation; T50pyr_CH: temperature for 50% conversion of SOC to volatile hydrocarbons during pyrolysis; T50pyr_CO2: temperature for 50% conversion of SOC to CO_2 during pyrolysis; OI: oxygen index. Significant (nonparametric) Spearman correlations are illustrated by linear regression lines.

farms when these were analyzed separately, but not for conventional farms. We do not conclude that multifunctionality is unresponsive to management intensity in conventional fields but foresee that conventional farmers will need to explore novel approaches to reduce their management intensity to enhance soil multifunctionality.

Although sensitivity analysis confirmed that multiple components of agricultural practice and soil functionality contribute to the broader relationships, the approach masks underlying mechanisms that may require targeted investigation to demonstrate individual effectiveness. Reduced tillage frequency and the use of grass-legume cover crops influenced multifunctionality most, suggesting that these practices will contribute to greater soil health (*5*) in both organic and conventional agriculture. Our results support less-intensive management to increase soil health in high-yielding agricultural land. In this context, the paradigm of sustainable intensification may be contradictory because management intensification undermines soil multifunctionality. We propose that "productive deintensification" is a more appropriate aim, meaning "an optimization of yield while reducing management intensity."

Locating this study in the Netherlands has implications for the scale of management intensity that we observed, and our results and conclusions should be seen in the context of high-intensity, high-yielding agriculture prevailing in northwestern Europe. In particular, several components of management intensity may be considerably lower in regions where agriculture is less industrialized (*36*). By contrast, both organic and conventional arable farms in the Netherlands have historically received considerably more animal manure than in many other regions (*37*). Furthermore, relationships between management intensity and yield are expected to vary between contrasting regions. Although no region can represent the variability of agricultural practice globally, the inverse relationship we observed between management intensity and multifunctionality across a large dataset suggests a general relevance for comparable contexts.

The weak relationship between soil biodiversity and multifunctionality contrasts with several other studies (*38*, *39*), but such relationships are not consistently observed within a single climatic region (*40*). Larger fauna, not considered here, may influence multifunctionality (*5*). However, these organisms strongly influence soil microbial communities (*41*), and we found little correspondence between microbial abundance and multifunctionality or between diversity and multifunctionality. Our results also indicate that biodiversity is less important for multifunctionality than the functions provided by the biotic community (*42*), which might be better characterized by metagenomic or metatranscriptomic analysis or food-web structure (*43*).

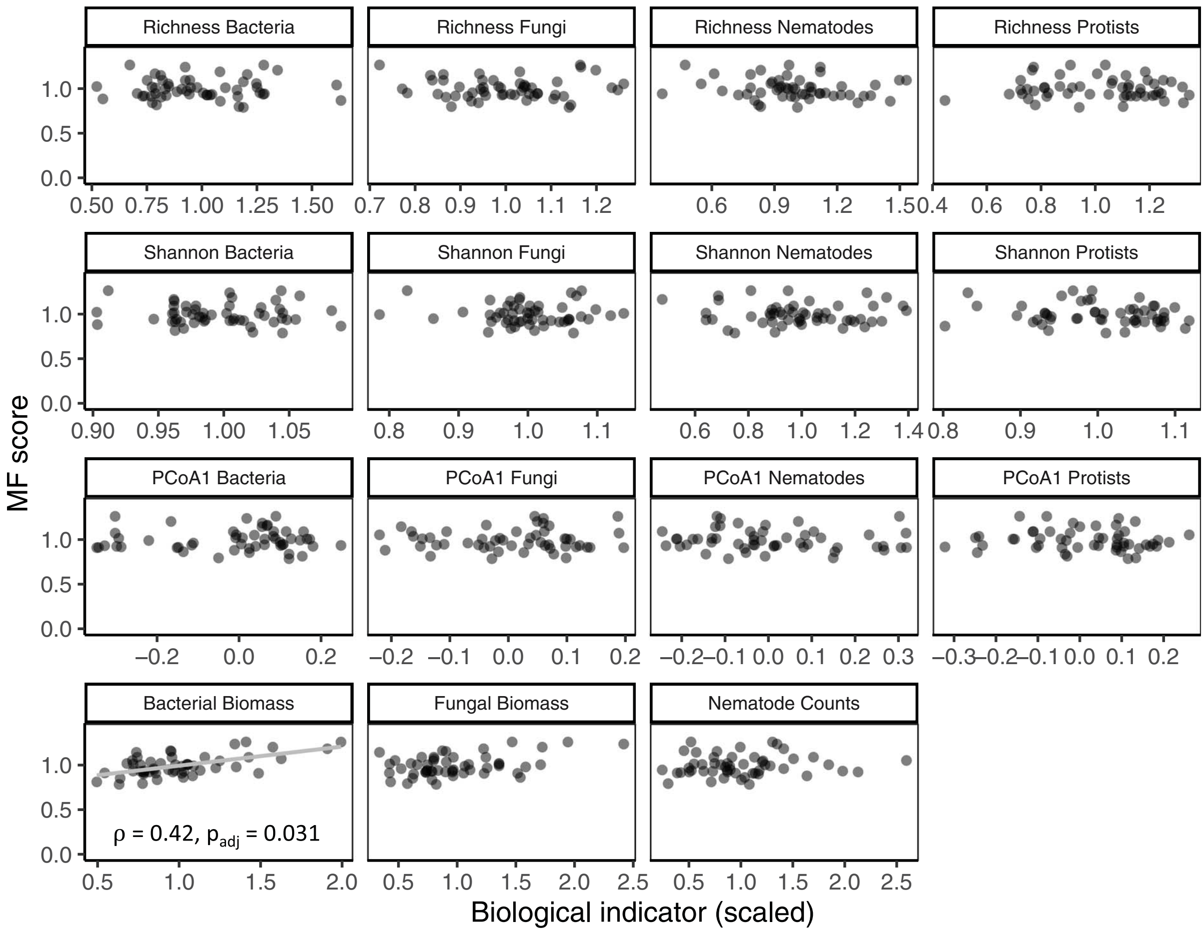

Fig. 4. Relationships between soil biological parameters and soil multifunctionality. Biological parameters are scaled to the mean of the respective soil type, consistent with the scaling applied to the multifunctionality indicators. Significant (nonparametric) Spearman correlations are illustrated by linear regression lines.

We observed robust associations between SOC properties and soil multifunctionality (tables S7 and S8), with total SOC contents, followed by POMC content, as the strongest predictors. Notably, POMC content (and marginally total SOC) was also negatively related to management intensity, corroborating the responsiveness of this pool to management (*44*) and suggesting that it may be an important mediator of management effects. Our results support the straightforward use of total SOC content as an integrative indicator of soil multifunctionality that is not only easily and widely measured but also the best predictor among a wide range of SOC properties (*29*).

If soil multifunctionality is enhanced by reducing management intensity, the question arises whether yield can be simultaneously sustained to preserve productivity and farm economic viability. This is particularly relevant when considering increasing regulatory restrictions on fertilizer inputs and pesticides. Crop differences, variable allocation to harvested biomass, and confounding weed cover make NDVI a coarse proxy for yield. Nonetheless, as an approximation of plant productivity (*32*), NDVI did not show any significant relationship to management intensity or multifunctionality. We also note that some fields achieved high scores across multiple multifunctionality indicators, several of which support plant productivity. This finding suggests that stringent trade-offs need not arise between multifunctionality and yield. Confirming this will require empirical work to verify causal relationships between practices and functions, in which long-term consequences for agronomic and environmental performance are monitored. Ultimately, soil multifunctionality will need to be optimized under local environmental conditions to enhance the sustainability of food production systems. Our results suggest that this might be best achieved not by targeting sustainable intensification but rather productive deintensification.

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SUPPLEMENTARY MATERIALS

science.org/doi/10.1126/science.adr0211
Materials and Methods
Figs. S1 to S7
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MDAR Reproducibility Checklist

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