Agricultural Systems 234 (2026) 104689

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Determinants of yield variation of organic cereals in productive agricultural areas

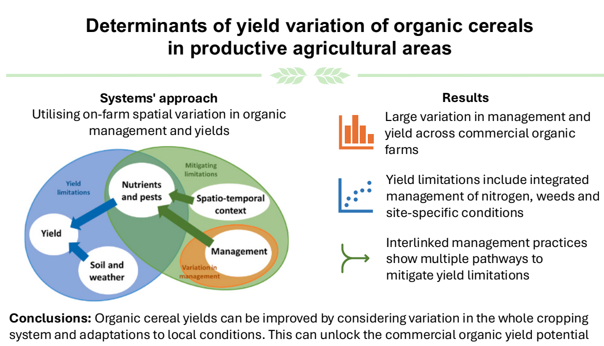
Rafaelle Reumaux [a,1,*], Melanie Karlsson [b,c,1], Romain Carrié [b,d], Ingrid Öborn [a], Christine A. Watson [a,e], Göran Bergkvist [a], A. Sigrun Dahlin [a], Johan Ekroos [b,f,g], Johanna Wetterlind [h], Henrik G. Smith [b,i]

[a] Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Box 7043, SE-750 07 Uppsala, Sweden
[b] Centre for Environmental and Climate Science, Lund University, Lund, Sweden
[c] University Library, UiT The Arctic University of Norway, Tromsø, Norway
[d] Dynafor, INRAE, Toulouse, France
[e] Rural Land Use, SRUC, Craibstone Estate, Aberdeen, United Kingdom
[f] Department of Agricultural Sciences, Plant Production Sciences, University of Helsinki, Helsinki, Finland
[g] Helsinki Institute of Sustainability Science, HELSUS, University of Helsinki, 00014 Helsinki, Finland.
[h] Department of Soil and Environment, Swedish University of Agricultural Sciences, Skara, Sweden
[i] Department of Biology, Lund University, Lund, Sweden

HIGHLIGHTS

- Large span of variation in commercial organic yields indicates room for improvement
- A systems-view shows that yields are limited by both management and local conditions
- Focus within organic enables investigations of inherent management strategies
- Evidence of a large diversity in management practices adopted by organic farmers

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor name: Zhao Zhang

Keywords:
Cereals
Management
On-farm observation
Organic agriculture
Yield limitations

ABSTRACT

Context: Organic farming aims to make agriculture more sustainable, but its sustainability benefits may be offset by lower yields compared to conventional farming. Avenues to increase organic yields have been studied extensively, but there is a lack of research using integrated approaches that consider co-variation between different organic management practices within commercial farming systems. Moreover, organic farmers face diverse bio-physical constraints that experimental, plot-level studies, often fail to address in a system-level context.

* Corresponding author.
E-mail address: rafaelle.reumaux@slu.se (R. Reumaux).
[1] *Equally contributing first authors of this paper.*

https://doi.org/10.1016/j.agsy.2026.104689
Received 13 February 2025; Received in revised form 19 December 2025; Accepted 14 February 2026
Available online 23 February 2026

Objective: Our aims were to highlight and utilise existing variation among organic farms to understand the factors that limit yields, considering the entire cropping system and its context. This included crop management, biophysical conditions and spatio-temporal context.
Methods: For 56 commercial organic farms in southern Sweden, we mapped between-farm variation in management and how it related to cereal yields. We obtained data on crop yield and management practices from farmers, conducted field measurements of crop performance, available nutrients, and pests, and retrieved data on farming context from public land-use databases. In a two-step approach we investigated how management practices affect yield through the observed field constraints.
Results and conclusions: There was considerable variation in management practices between organic farms, which is often overlooked. Variation in cereal yields was primarily related to nutrient application and, to some extent, weed management. Yields were also explained by factors affected by more long-term management or even beyond the control of the farmer, such as soil organic matter, soil texture and weather. We conclude that there is potential to increase organic cereal yields, but that this requires consideration of the whole management system and adaptations to local conditions by individual farmers.
Significance: The yield-differential between organic and conventional farming has been argued to be an Achille's heel for organic farming. This study shows a large between-farm variation in management practices and yields in organic crop production that can help realizing the organic yield potential at farm and field level, strengthening organic farming as a tool for agricultural sustainability.

1. Introduction

Achieving sustainable food production is a major global goal (FAO, 2021) and organic farming systems can contribute to reach this goal (Eyhorn et al., 2019). Generally, organic farming has fewer negative environmental impacts (Reganold and Wachter, 2016; Smith et al., 2019) and higher provisioning of public goods and ecosystem services (Röös et al., 2018; Seufert and Ramankutty, 2017) than non-organic systems commonly referred to as conventional farming. At the same time, organic farming often has low yields per hectare (Kniss et al., 2016; Reganold and Wachter, 2016; Seufert et al., 2012; Seufert and Ramankutty, 2017; Smith et al., 2019). Additionally, organic farms usually have a high share of feed or non-food crops in their rotations, such as leys and green manure crops (Connor, 2018; Reumaux et al., 2023), that may create opportunity costs that reduce total production further (Alvarez, 2022; Barbieri et al., 2019). Taking the lower yields and lower total production into account, the environmental benefits of organic farming compared to non-organic or conventional systems may be reduced or even reversed (Meemken and Qaim, 2018; Seufert and Ramankutty, 2017; Tuomisto et al., 2012), as more land is required to produce the same amount of food (Connor, 2018). If not linked to dietary changes, this can result in agricultural expansion, with detrimental effects for environmental externalities, biodiversity conservation and ecosystem service provisioning (Green et al., 2005; Phalan et al., 2011). Although these potential trade-offs often result in concerns about the sustainability of organic farming in future agriculture (Kirchmann, 2019; Tscharntke et al., 2021), the potential for sustainably increasing yields in organic farming and thus alleviating the trade-offs has received little attention (Röös et al., 2018). This is particularly important in structurally simple and intensively managed landscapes, where the yield difference, as well as the marginal environmental benefits, of organic compared to conventional farming is largest (Smith et al., 2020). This may constrain conversion to organic farming in such areas, as is the case in Sweden, likely because the higher opportunity costs are not covered by current area-based subsidies (Rundlöf and Smith, 2006).

Understanding yield limitations and finding avenues for improving organic farming systems have usually been approached through comparison with non-organic farming systems (e.g., de Ponti et al., 2012; Ponisio et al., 2015; Seufert et al., 2012), with nitrogen limitation suggested as the main driver of the lower organic yields (Alvarez, 2022; Seufert et al., 2012). In contrast, studies assessing yield variation and limitations within organic farming systems themselves are scarce (Thorup-Kristensen et al., 2012), even though this would enable a deeper understanding of how to mitigate the environmental and economic concerns caused by low organic yields (Ponisio et al., 2015). Major studies focusing on arable crops address the fact that yield variability is higher in organic compared to conventional farming (Knapp and van der Heijden, 2018; Smith et al., 2019) and suggests that organic crop yields are more sensitive to variations in environmental conditions. However, this may also indicate a knowledge gap in specific management to improve organic yields. Studying the causes of variation in organic crop production is complex. Most previous studies have examined management practices in isolation rather than considering the entire cropping system (e.g. Ponisio et al., 2015; Seufert et al., 2012). However, in practice, management practices do not vary independently of each other but are combined according to the farmer's objectives and available resources, resulting in interactions and interconnected pathways that can produce varied and complex outcomes (Sebillotte, 1990). For example, Nkurunziza et al. (2020) found that a combination of previous management, landscape structure and soil quality can explain variation in barley yields and grain quality on organic farms. Similarly, Casagrande et al. (2009) identified multiple determinants of organic barley protein content, including cultivar, crop nitrogen status and weed coverage. However, variations in management and yield between fields and farms are inherently linked to factors in agricultural systems not under the short-term control of farmers, such as variation in soil characteristics, landscape features and climate conditions (Seufert et al., 2012).

A further limitation of many studies of organic farming is their reliance on experimental conditions which often include high nitrogen inputs from manure or other sources, conditions that do not reflect the typically limited nitrogen supply in commercial organic systems (Döring and Neuhoff, 2021), or indeed other constraints that commercial farmers may face. Where commercial data are included, they often consist of national-level farm statistics (e.g. Kniss et al., 2016), which limits the possibility to directly link specific management practices to yield outcomes. Studies on commercial farms that consider soil type, climate and local management practices allow interpretations that are closer to the farmers' reality and help bridge the gap between research and practice, therefore facilitating the dissemination of knowledge among farmers and stakeholders (Lacoste et al., 2022). Similar studies have previously integrated farmers' observations with modelling and performance evaluation to guide context-specific decisions in non-organic farming (e.g. Carberry et al., 2002; Cock et al., 2011; Jiménez et al., 2016). Bundling of management practices, context dependence of consequences of management choices and need of realistic options available to farmers, call for a systems approach based on context-specific studies that enables the capturing of effects of real-world management practices and environmental variations on crop yields across farms at large spatial scales. Whereas traditional factorial experiments often fail to capture the complexity of interactions among soil, climate, and management that drive production, we here use an approach reflecting a recent shift in agronomic research, by using real-world commercial farm data to unravel the multi-factor interactions that influence crop productivity.

Arable agricultural systems are often dominated by cereal crops. These crops are profitable cash crops, which are important in both human and animal nutrition. Spring barley (*Hordeum vulgare L.)* and winter wheat (*Triticum aestivum L.*) are commonly grown cereals in organic production systems in Sweden. Wheat is typically prioritised in management (Reumaux et al., 2023) due to the significant price difference based on protein concentration, while barley is more commonly aimed to be used as feed. Hence, understanding the limitations to the productivity of these two crops can help identify key factors influencing profitability in organic systems and ultimately encourage farmers to transition to organic farming.

To investigate the consequences of management-yield relationships against a backdrop of large-scale variation in biophysical conditions, we conducted a study on organic farms in two productive agricultural areas in southern Sweden. The study focuses on spatial (between farm) variation in field management and yield of organic spring barley and winter wheat. We adopted a systems approach, where we combined observation plots in commercial spring barley and winter wheat fields with a survey of farmers' current management practices of the fields and accounted for background variations driven by factors outside the short-term control of farmers. We had the following two aims:

(1) Identify key patterns and linkages between management practices to understand the complexity and diversity inherent to organic farming systems.

(2) Uncover ways to improve organic crop productivity by analysing the agronomic, ecological and bio-physical components of the systems and how they relate to yield.

2. Materials and methods

2.1. Study area and study design

We performed the field studies in 2020 in two productive agricultural areas of southern Sweden (Fig. 1), including the arable plains in the provinces of Skåne and Halland, and Västra Götaland. Both areas are dominated by non-organic agriculture, mostly specialised in the production of annual crops (Swedish Board of Agriculture, 2022).

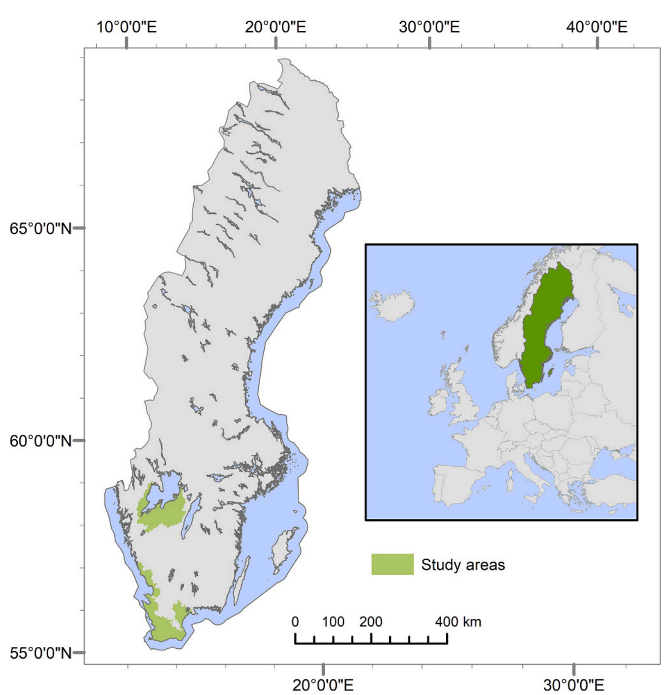


Fig. 1. Map indicating areas in which studied farms were situated.

Since the share of arable organic farming was low in the selected areas (Swedish Board of Agriculture, 2022), we contacted all organic farms larger than 10 ha that had been managed organically for at least four years and that grew either spring barley or winter wheat the year before. In total, 56 farms still grew either one or both desired crops organically in 2020 and were willing to participate in the study. On each farm, one field per crop was selected to represent typical conditions and management practices of the farm, based on descriptions by the farmers. This resulted in 52 fields of spring barley (26 in each area) and 29 fields of winter wheat (12 in the southern and 17 in the northern area).

The area of arable land on the 56 farms ranged from 18 to 1000 ha, with most farms (82%) also having livestock production. Based on normal yields reported by the farmers, crop yields in 2020 were similar to normal ones for both spring barley (paired *t*-test: $t50 = 0.59$, $p = 0.55$) and winter wheat ($t27 = -0.66$, $p = 0.52$). In 2020, mean annual temperature at the study locations was 2.4–2.8 °C higher than the 30-year average (Swedish Meteorological and Hydrological Institute, 2024). Total precipitation ranged between 600 and 1000 mm for the whole year, which was similar to or slightly above the 30-year average (600–800 mm; Swedish Meteorological and Hydrological Institute, 2024).

2.2. Field data

To directly observe yield limitations and productivity in the fields, we established four plots (2 × 2 meters) at least 25 m away from any field border and from each other. These plots were placed to reflect the heterogeneity within the field, as an indicator for this we used the variation in soil clay content from a digital soil map of arable land in Sweden (validated on multiple scales; Piikki and Söderström, 2019). Each field was visited three times during spring and summer 2020, throughout the crop growth cycle from tillering to grain maturity, to collect indicators of crop performance, nitrogen status using a SPAD chlorophyll meter (Follett et al., 1992), weed abundance as estimated by ground weed coverage, aphid abundance and proportion of leaves with symptoms of disease (for detailed information, see Table S1 in Supplementary Material (SM)). The first visit was done in late May to early June (growth stages BBCH 20–48 for spring barley and 24–57 for winter wheat; BBCH according to Lancashire et al., 1991), the second was late June to early July (BBCH 51–85 for spring barley and 61–87 for winter wheat), and the third was in mid-July to very early August (BBCH 77–93 for spring barley and 85–93 for winter wheat). We aimed to reduce the difference in crop development stage between fields within the same sampling round by visiting the farms in the order of sowing date of spring barley.

For analyses we selected the crop development stage at which each field variable was at is key stage to affect yield. For nitrogen status, we used data from the first visit to represent conditions when yield quantity is determined (Le Bail et al., 2005). For disease and weed abundance, we used data collected during the second visit, since at that time we expected leaf spot disease symptoms to peak and most weeds to have established, while being early enough in the season to reflect relevant interspecific competition with the crop. Aphid abundances were invariably very low, with 53% of fields having no aphids, 7% of fields having more than one aphid per tiller and the most infested field having 2.2 aphids per tiller. Therefore, we did not consider aphid infestation in the statistical analysis.

To acquire detailed information of the soil nutrient status and other soil parameters in each plot, we sampled the topsoil (0–20 cm) during the third visit, shortly before harvest of the cereal crop. Nine subsamples were collected in each of the four plots per field, in a zig-zag pattern and pooled together. Fresh soil samples were sieved (2 mm) and air-dried at 20–25 °C for 48 h and then analysed for plant-available potassium and phosphorus (using ammonium acetate-lactate extraction method; Egnér et al., 1960), pH (1:2.5, H2O; SIS, 2005), and loss on ignition as an indicator of soil organic matter (SOM) content (Howard and Howard, 1990). Soil parameters such as pH, plant-available phosphorous and potassium exhibit relatively slow temporal variability, and form a robust basis for management recommendations for commercial farmers in the subsequent growing season (Andersson et al., 2022).

2.3. Farmer management practices

To gather detailed information on the main field operations during the growing season of spring barley (2020) and winter wheat (2019–2020), each farmer was interviewed by phone during the following winter. We obtained information about farm characteristics, time since transition to organic farming practices, yield and grain use, and crop management of the fields monitored, such as sowing dates, soil tillage, weed control methods, type and amounts of fertilisers used, preceding crop and crop rotations (Table S1). From the information obtained about fertiliser application, we estimated nitrogen inputs from fertilisation. For manure-based fertilisers, we used information about available nitrogen content from guideline values (Swedish Board of Agriculture, 2015).

For biogas digestate, where nutrient composition varies markedly between biogas producers, we used estimates of nitrogen content reported by the farmers. For other types of non-manure fertilisers (commercial products made from by-products from the food industry), we combined the farmers' report on amounts used with the content of total nitrogen given for each product by the producer.

2.4. Farming conditions from external data

Local weather at each field was taken into account through temperature and precipitation calculated from gridded Copernicus data (0.1-degree regular grid; *E*-OBS database; Cornes et al., 2018). The growing season used was 19 April-1 August 2020 for spring barley and 27 September 2019–1 August 2020 for winter wheat. Daily precipitation was summed over the growing season and daily temperatures were used to calculate cumulative growing degree days (GDD) from daily mean temperatures exceeding 4.5 °C.

An estimate of the average soil clay content of each field was extracted from a digital soil map of arable land in Sweden (50 × 50 m; Piikki and Söderström, 2019), by averaging across all raster cells within the fields. The landscape context surrounding each field, important for many ecosystem services such as pest control, was calculated as the proportion of arable land within 1 km from each field's centre using the Swedish National Land Cover Database (Swedish Environmental Protection Agency, 2018).

2.5. Statistical analyses

We developed a conceptual framework (Fig. 2) to structure the analyses. This framework starts with understanding patterns in organic management practices (orange circle in Fig. 2) and continues with identifying organic yield limitations (blue circle in Fig. 2) and how these limitations can be alleviated by management practices (green circle in Fig. 2). This framework was developed to both give a mechanistic understanding of management strategies and yield limitations whilst at the same time allowing for comprehensive analyses with a limited sample size. All analyses were carried out using R Statistical Software (v4.2.3; R Core Team, 2021), with the two crops analysed separately. The two regions were analysed together to generate generalizable results and maintain statistical power. But to avoid results being driven by mean differences between the two areas, we group mean-centered data based on the regional averages for each variable (using the package 'misty'; Yanagida, 2023), a common approach in multilevel data analyses (Bell et al., 2018). For improved interpretability of variables, we adjusted them back to their original scale after analyses, by centering around the global mean (i.e. adding the global mean to the deviation from the regional mean). To enable group-mean centring of the preceding crop, which is a factor variable, we converted it into a continuous variable and expressed as expected yield increase. This "pre-crop effect", according to Andersson et al. (2022) was estimated as the additional nitrogen available to the following crop, based on residual soil nitrogen, improvements in soil structure, and disease-suppressing effects of the preceding crop. The dataset from this study is available at https://doi.org/10.5878/z95f-6h51, both in its original form and group mean centered.

First, to explore the variation in management practices across farms, we summarized the practices value range and then used Principal Component Analysis (PCA) to determine their joint distributions. This reveals patterns between management practices since they might be associated with each other, due to farmer choosing to combine practices

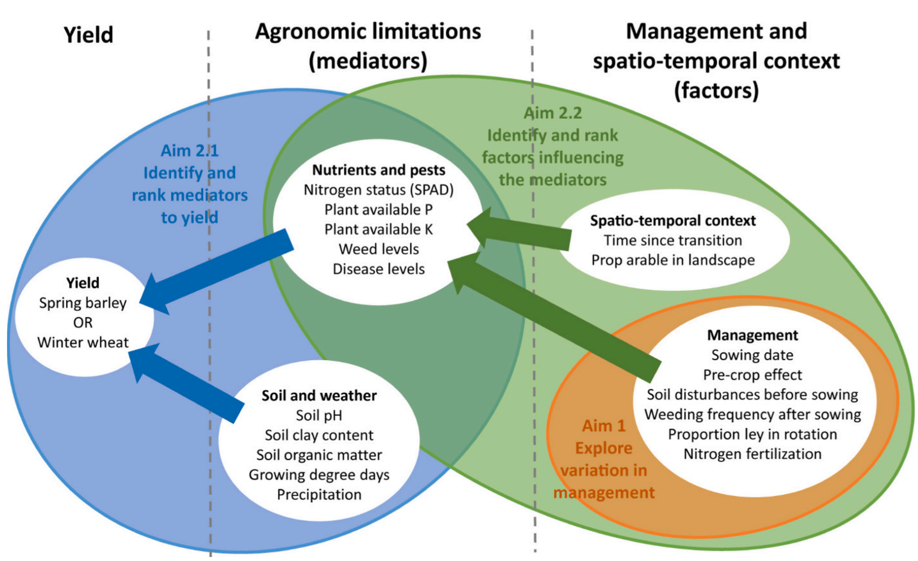


Fig. 2. Conceptual framework used to guide our analysis. First, we describe and explore the variation and patterns of management practices in organic farming (aim 1, orange circle). Secondly, we aim to understand organic crop productivity (aim 2). This was analysed through a two-step process, first by analysing and ranking the effect of biophysical limitations (mediators) on yield of spring barley and winter wheat (blue circle) and secondly analysing the effect of management and spatio-temporal context as drivers of the yield mediators that can be influenced by short-term management choices (green circle). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to reach certain production objectives (Sebillotte, 1990) or might be typical of certain farming contexts, environments and farming history (Roschewitz et al., 2005). The PCA was conducted on unit-scaled variables using the R function prcomp. To interpret the PCA, we examined the relationship between each principal component and the field-specific management variables based on the loadings, highlighting important variables with loadings above 0.3 (absolute value) in the table.

To achieve our second aim, understanding yield limitations, we used a two-step approach inspired by Casagrande et al. (2009). In the first step, we included variables that directly influence yields, rooted in biophysical and agronomic limitations, which we call 'yield mediators' (Fig. 2). These concern nutrients (nitrogen approximated by leaf chlorophyll, plant available phosphorus and potassium in the soil), pests (weeds, diseases and pests), soil characteristics (clay content, pH and organic matter) and weather (precipitation and growing degree days).

The mediators include both those directly related to variables that farmers can significantly influence by short-term management decisions (nutrients and pests), and those related to variables that are primarily affected by nature-given conditions or historical management (soil characteristics and weather). In this step, one spring barley field was excluded as it was harvested before grain maturity for fodder use. In the second step, we individually explained the yield mediators of nutrient and pests by mainly short-term crop management practices and the spatio-temporal context of the field (Fig. 2). We call these 'factors affecting yield mediators'. This step included the following explanatory variables: sowing date (for spring barley), preceding crop effect, proportion of ley in the crop rotation, nitrogen fertilisation, soil disturbance (cultivation) before sowing, weed control after sowing, time since transition to organic farming and proportion of arable land in the landscape. Sowing date of winter wheat could not be used, as there were too many missing values. Accounting for the different cultivars at this stage would have been desired due to their different characteristics and performance (Callaway, 1992; Ficiciyan et al., 2018). However, this was not possible because of the large number of cultivars used among the farmers and the low level of replication (if any) across the study. While soil pH and SOM can be affected by management the effect of short-term management was assumed to be negligible since lime had not recently been applied on any of the fields and SOM is mainly affected by long-term management. Soil pH and SOM were therefore not considered as responses in this step (Fig. 2; compare with Jiménez et al., 2016).

To identify and rank the most important yield limitations and management constraints we used multi-model inference (Burnham and Anderson, 2002; Grueber et al., 2011) based on bias-corrected Akaike Information Criterion (AICc) (dredge-function from 'MuMIn' package; Barton, 2022). Based on the distribution of the data, our fully specified models as input to the multimodel inference were linear regression (LM) models on farm-level data assuming Gaussian error distributions. This excepted the models of weed and disease abundance, which are measured as proportions (proportion weed coverage and proportion affected leaves) and thus beta regressions were more suitable ('betareg' package; Cribari-Neto and Zeileis, 2010). To improve model conformity, all explanatory variables were standardised (z-transformation) and available potassium as a response was log transformed for spring barley, but not for winter wheat. In each model, the explanatory variables were ranked using relative variable importance, which was calculated as the sum of model Akaike weights over all models that included each explanatory variable (Giam and Olden, 2016). This approach is recommended for handling uninformative variables when the aim is to investigate the relative importance of many predictors (Arnold, 2010). We extracted variable coefficients and errors from the best competing models (within two AICc). We then averaged effects across only the models where it appeared, based on conditional average, this way we could determine the absolute effect size and avoid a reducing bias (Galipaud et al., 2017; Nakagawa and Freckleton, 2011). The variable coefficients and errors are illustrated in petal plots, and in addition we graphically present the best model's effects and raw data in scatterplots ('effects' package; Fox and Weisberg, 2019). Model performance and assumptions of normality and residual distribution were checked using DHARMa (Hartig, 2022) for linear regression models and visual inspection of plots (base-R) for beta regression models, all conforming. For all models, we checked for multicollinearity (all VIF values were below 3.2). We also checked for potential influential data points using the 'car' package (Fox and Weisberg, 2019), using Cook's distance to reveal them (Cook's D $>$ 0.5). The test identified two potentially influential data points in the models on factors affecting yield mediators of winter wheat that related to nitrogen status and plant-available potassium. We ran the ranking and model averaging with and without these data points and obtained additional affecting variables when they were included. The results presented below omit the influential data points, while results including the influential points are provided in Table S2.

3. Results

3.1. Variation and patterns in management of spring barley and winter wheat

Yields of both spring barley and winter wheat varied considerably between farms, with a three- to four-fold difference between the lowest and highest yields, accompanied by considerable variation in management of both crops (Table 1, Fig. S1). The amount of nitrogen added as fertiliser ranged from 0 to 88 kg/ha (mean $\pm$ sd, 37 $\pm$ 25 kg/ha) for spring barley and from 0 to 160 kg/ha (79 $\pm$ 41 kg/ha) for winter wheat. A wide range of fertiliser types were used, of both manure and non-manure origin, including cattle and pig manure, by-products from the food industry and biogas digestate.

The most common pre-crops to spring barley were cereal crops (48%) and ley (31%), whilst for winter wheat, ley and cereal crops were almost equally common (34% and 31%, respectively). When a fixed rotation was applied, the crop rotation ranged in length from two (cereal-pasture) to eight years. For both crops, most fields were ploughed before establishment, while the number of non-weeding related soil disturbances (cultivations) before sowing ranged from none to seven for spring barley and none to six for winter wheat. The number of weeding operations ranged from none to three or four (winter wheat and spring barley, respectively). For 20 out of 52 spring barley fields, the harvested grain was intended for seeds or human consumption (e.g. beer or whisky), while the corresponding figure for wheat was 16 out of 29 fields.

Spring barley.

The first three PCA axes explained 50% of the variation in spring barley management (Table 2, Fig. S2). PC1 explained 18% of the variation and was mainly driven by having no undersowing, frequent weeding and being organic for a long time. PC2 was associated with frequent weeding, few years of ley in the rotation and the harvested grain being intended for food or seed purposes. PC3 was associated with later sown fields, long rotations, few soil cultivations and generally higher fertilisation. When considering all three components, the most important factors describing the variation in management of spring barley fields were use of undersowing, crop rotation length, sowing date and frequency of weeding after sowing.

Winter wheat.

Winter wheat management was explained to 64% by the first three PCA axes. PC1 explained 27% of the variation (Table 2, Fig. S3) and was associated with fields with many years of ley in the rotation, frequent weeding, high fertilisation and high precrop effect. PC2 reflected frequent soil disturbances before sowing and undersown fields. PC3 related to recently converted organic farms intending to use the harvested grain for food or seed purposes, frequent weeding, low fertilisation and undersowing. When considering all three components, the most important factors describing the variation in management of winter wheat were the planned use of the crop, time since transition to organic

Table 1
Description of management variation in spring barley (SB) and winter wheat (WW) fields included in the two study regions. Mean values are presented for continuous variables and median for discrete variable, plus the range for both variable types.

		Spring barley fields ($n = 52$)		Winter wheat fields ($n = 29$)	
Variable	**Description, units**	**Mean (continuous) or median (discrete)**	**Range**	**Mean (continuous) or median (discrete)**	**Range**
Grain yield	Field level yield, kg/ha	3766	1500–7000	4463	2000–7000
Time of transition to organic farming[1]	Year of conversion of the field	2005	1950–2019	2004	1992–2016
Sowing date (known for 10 of 29 winter wheat fields)	Day number (in 2020 for SB and 2019 for WW)	111	80–136	267	262–293
Sowing density	kg seeds/ha	216	160–450	225	170–300
Nitrogen fertilisation[2]	Applied kg N / ha	37	0–88	79	0–160
Pre-crop effect (estimated yield increase by the pre-crop from Andersson et al., 2022)	kg grain/ha	231	0–800	690	0–1200
Mechanical weeding operations after sowing	Number of times per field	0	0–4	0	0–3
Soil disturbances (cultivations) before sowing (excl. ploughing)	Number of times	3	0–7	2	0–6
Length of crop rotation, if fixed rotation applied[3]	Number of years	6	2–8	6.5	3–8
Ley length in crop rotation	Number of years	3	0–5	3	0–5
Cultivar	Number of cultivars	14 different cultivars		8 different cultivars	
Row spacing	Width between sown rows	49 narrow (10–12.5 cm), 2 wide (24-25 cm), 1 irregular		25 narrow (12–12.5 cm), 4 wide (24-25 cm)	
Seed treatment	Use of heat- treated seed	13 yes, 33 no, 6 don't know		8 yes, 19 no, 2 don't know	
Undersown crop	Number of fields where ley was undersown into the studied crop field	20 yes, 32 no		9 yes, 20 no	
Main mechanical weeding strategies	Whether weeding after sowing was done by harrowing or hoeing	20 (fields with) harrowing, 2 row hoeing, 30 none		10 harrowing, 4 row-hoeing, 15 none	
Ploughing	Ploughing before the studied crop or no-till	50 yes, 2 no		29 yes, 0 no	
Source of fertilisers used	Manure, non-manure or a combination	26 manure, 14 non-manure fertilisers, 7 combinations, 5 unfertilised		13 manure, 6 non-manure fertilisers, 10 combinations	
Fertilisers	List of types	Cattle manure Poultry manure Pig manure Horse manure Sheep manure Byproducts from food and farm industry Biogas digestate		Cattle manure Poultry manure Pig manure Horse manure Sheep manure Byproducts from food and farm industry Biogas digestate	
Preceding crops	List of crop types	25 cereal, 16 ley, 6 grain legume, 2 potato, 1 maize, 1 pasture, 1 mix of cereal and legume		10 ley, 9 cereal, 6 oilseed rape, 2 grain legume, 1 sugar beet, 1 potato	
Intended use of the grain	Feed, food or seed	32 feed, 20 food or seed		13 feed, 16 food or seed	

[1] The farm had to be organic since at least four years before the study, however individual fields may be converted more recently than this.
[2] Calculations were based on available nitrogen for manures and total nitrogen for non-manure sources.
[3] One spring barley field did not have a fixed crop rotation.

practices and the frequency of weeding of the field.

3.2. Identification of mediators affecting crop yield

Spring barley.

The highest ranked predictors of spring barley yield were low soil organic matter content, low weed cover, high pH, and low soil clay content. Followed by high leaf nitrogen status, low concentrations of available potassium and high concentrations of available phosphorus in the soil (Fig. 3a and 4, Table S3). Disease abundance showed a weak negative relationship with spring barley yield and high standard error (Table S3). Precipitation and growing degree days did not contribute to explaining the variation in spring barley yields (Fig. 3a).

Winter wheat.

The highest ranked predictors of high winter wheat yield were high leaf nitrogen status, high soil organic matter and low precipitation (Fig. 3b and 5, Table S4). High growing degree days, high plant-available potassium, high soil pH and low clay content were also contributing to explaining winter wheat yield (Fig. 3b and 5, Table S4), while plant-available phosphorus, weed and disease abundance did not (Fig. 3b, Table S4).

3.3. Factors affecting important mediators of yield

Spring barley.

High weed cover in spring barley was mainly related to a low proportion of arable land in the landscape and late sowing date, followed by many years of ley in the crop rotation, low frequency of weeding and low pre-crop effect (Fig. 6b, Table S5 and Fig. S4). However, the pre-crop effect was highly uncertain, with the standard error being larger than the slope (Table S5). High nitrogen status in spring barley leaves was primarily related to late sowing date and high pre-crop effect, but also to some extent high proportion of arable land and low frequency of soil disturbances before sowing (Fig. 6a, Table S5, Fig. S5). High concentrations of available potassium in the soil were mainly related to a high proportion of arable land in the landscape, and somewhat to a low pre-crop yield effect and few soil disturbances before sowing (Fig. 6c, Table S5, Fig. S6). Ley length in the crop rotation showed a weak positive relationship, with a high standard error, to the levels of available potassium (Table S5, Fig. S6). Finally, high levels of available phosphorus in the soil were mostly related to fields with late sowing, high frequency of weeding after sowing and high proportion of arable land in the landscape (Fig. 6d, Table S5, Fig. S7). Frequency of soil disturbances before sowing and nitrogen fertilisation showed a weak and highly uncertain relationship to soil phosphorus levels (Fig. 6d, Table S5, Fig. S7).

Table 2
Percent total variation (contribution) and the principal components (absolute factor loadings) for management practices for spring barley and winter wheat fields.

	Spring barley			Winter wheat		
	PC1	**PC2**	**PC3**	**PC1**	**PC2**	**PC3**
Contribution rate	0,18	0,17	0,15	0,27	0,21	0,15
Cumulative contribution rate	0,18	0,35	0,50	0,27	0,48	0,64
Eigenvalue	1,34	1,31	1,24	1,57	1,38	1,16
Sowing date	−0,08	0,27	−0,43*	–	–	–
Weeding frequency after sowing	0,33*	0,48*	0,25	0,44*	−0,24	0,36*
Years in crop rotation	0,13	−0,25	0,64*	−0,10	0,60*	0,02
Years of ley in rotation	0,26	−0,51*	0,03	0,49*	0,11	0,18
Frequency of soil disturbances before sowing	0,22	−0,04	−0,43	0,19	0,59*	−0,03
Nitrogen fertilisation	−0,19	0,27	0,33	−0,26	−0,01	0,39*
Time since transition	0,50*	−0,01	−0,15	0,40*	0,25	−0,44*
Undersowing	−0,64*	−0,04	0,01	0,13	−0,10	−0,47*
Pre-crop effect	−0,22	−0,11	−0,11	0,05	0,34*	0,50*
Intended use of harvest grain	0,09	0,53*	0,11	0,52*	−0,20	0,14

* PC loadings with absolute value greater than >0.3.

Winter wheat.

For nitrogen status in winter wheat the factors of high nitrogen fertilisation and high weeding frequency after sowing ranked the highest. The relationships to pre-crop effect and proportion of arable land were small (Fig. 7a, Table S6, Fig. S8). Plant-available potassium in winter wheat was primarily related to high proportion of arable land, many years of ley in the crop rotation and long time since transition to organic farming, a relationship with nitrogen fertilisation is possible but highly uncertain (Fig. 7b, Table S6, Fig. S9).

4. Discussion

By capitalising on the full complexity of farming contexts and the wide diversity of management choices among commercial organic farms (Table 1), our two-step analytical approach (Fig. 2) enabled us to determine the main factors limiting yields of the two main organic cereal crops in Sweden. The large yield variations observed in both spring barley and winter wheat were related in part to factors outside the short-term control of the farmer, such as inherent field properties and climate, and to factors potentially directly relating to farmers' management choices, such as nutrient status and weed pressure (Fig. 3). Importantly, we could mechanistically show how these in-field, yield-limiting mediating effects were linked to several interconnected management decisions made by the farmers (Figs. 6 and 7).

4.1. A system's approach to uncover the diversity of organic management practices

We focus on comparisons within organic farming systems, in contrast to the predominant focus on comparing organic and conventional systems (e.g. Seufert et al., 2012). This approach allowed us to uncover the nuances of organic practices and identify strategies that may improve crop performance without using those of non-organic farming as standards. As such, our study provides evidence of the diversity of organic management practices used across commercial farms in varying pedo-climatic conditions. In fact, our results demonstrate a wide range of strategies related to fertilisation and weed management, which do not fall into distinct farm type classifications, as seen in other studies (e.g. Darnhofer et al., 2005; De La Cruz et al., 2023). Hence, our results underscore the variability and thus adaptability of organic management practices.

For both cereals, we found similar strategies for weed management related to the intended use of grain, with high frequency of post-sowing weeding for cereals destined to human consumption, while those intended for feed were less often weeded. However, spring barley and winter wheat differed in which type of cropping systems this weeding strategy was implemented. Spring barley grains for human consumption were grown in fields with intensive crop rotations (fewer leys relative to annual crops), while winter wheat was grown in fields with more complex crop rotations (longer leys) on farms with a longer history of organic management. This result is consistent with a Swedish national-scale study, in which spring barley in organic farms was more likely grown after a cereal, while winter wheat was rather grown after a ley (Reumaux et al., 2023). Furthermore, our study shows that the strategy of including winter wheat in more complex crop rotations was implemented mostly by experienced organic farmers (i.e., longer time since transition) growing wheat for human consumption. Organic winter wheat cultivated after a grass-legume ley are more likely to reach the protein content required by bread industry because of higher nitrogen-rich plant residues left in the soil (Casagrande et al., 2009) and lower crop-weed nitrogen competition due to the weed-supressing effect of leys (Martin et al., 2020). The protein content threshold is challenging to reach in organic farming (Casagrande et al., 2009) and, as our results

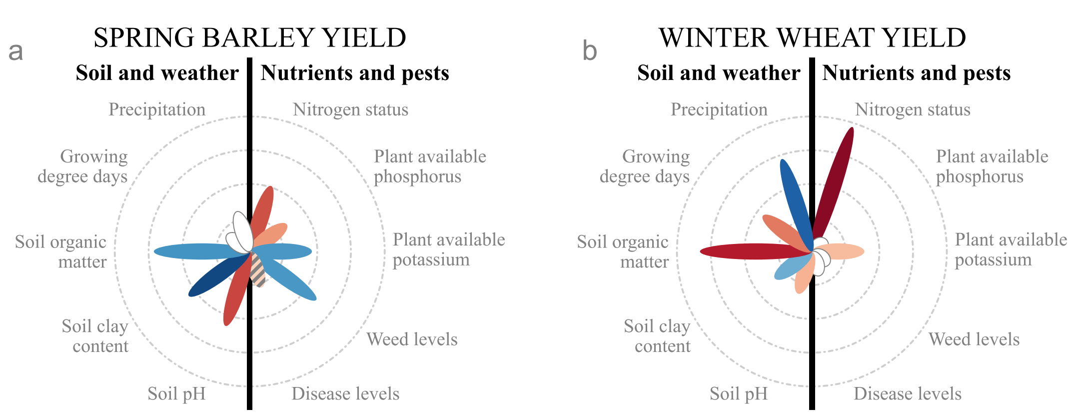


Fig. 3. Importance of yield mediators in (a) spring barley and (b) winter wheat. Petal length indicates the relative importance of the mediator relative to others (sum of weights), where concentric circles represent relative importance of 0.25, 0.5, 0.75 and 1, respectively. White petals show variables that were not included in any of the best competing models. Negative effects are presented in blue and positive in red. The colour intensity increases with the relative slope of the relationship. Grey striped petal indicates uncertain effect where the standard error of the slope was larger than the slope. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

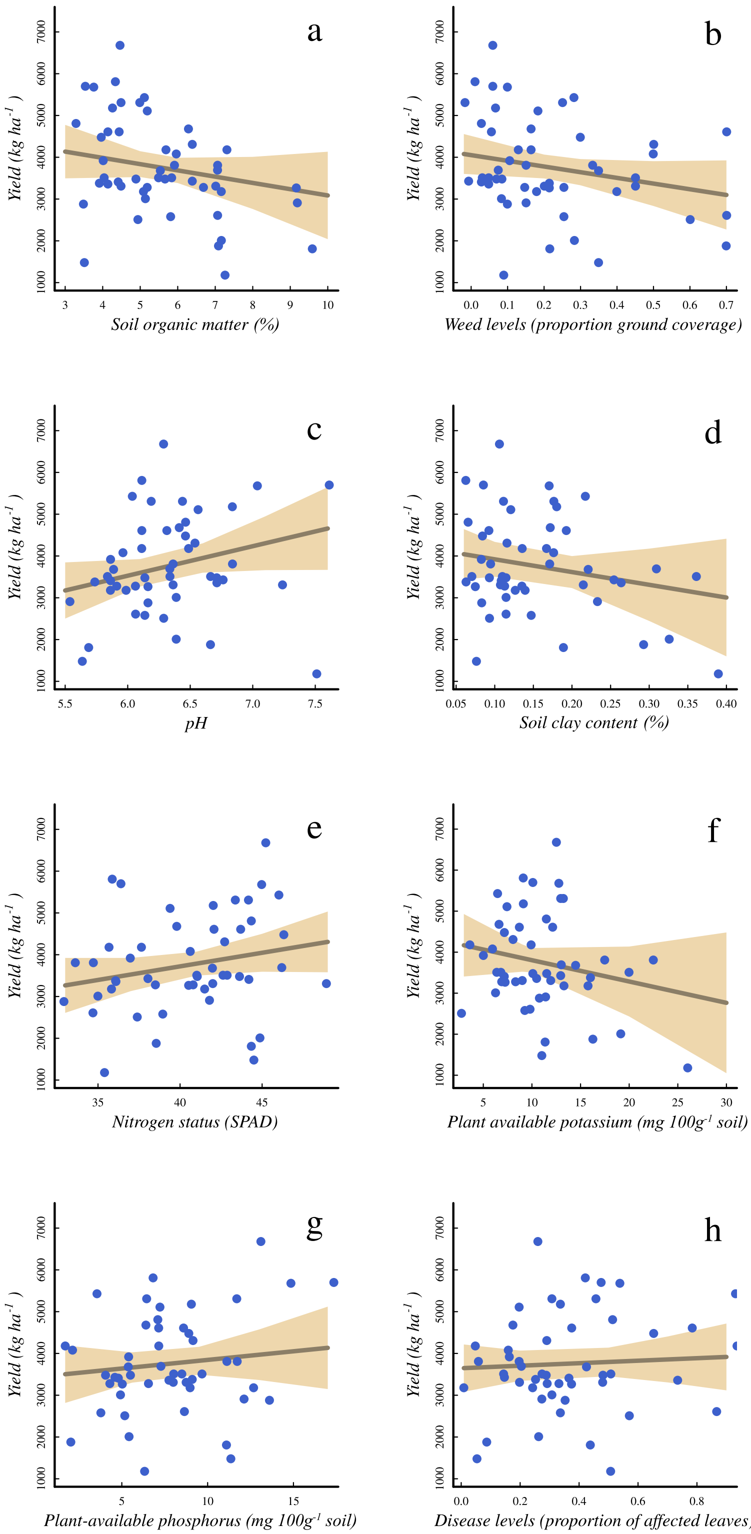


Fig. 4. Data and modelled effects of mediators of spring barley grain yield: (a) soil organic matter, (b) weed abundance, (c) soil pH, (d) soil clay content, (e) nitrogen status, (f) plant-available potassium, (g) plant-available phosphorus, and (h) disease abundance. The line and shading shows effects and 95% confidence interval for the averaged linear model, with raw data shown as dots.

suggest, these challenges can be associated with technical difficulties that farmers with a long experience of organic conditions are more likely to solve. In contrast, although farmers may be less likely to optimize the position of organic spring barley in the rotation in relation to the pre-crop (Reumaux et al., 2023), we show here that the intended use of barley grain is likely to affect weeding strategy.

Finally, some practices covaried across organic farms, most notably the frequency of soil tillage and crop rotation length for winter wheat. As rotation length and the length of leys in the rotation were not related in winter wheat, it is possible that longer rotations implied more annual crops on average, so that more mechanical weeding and soil-improving interventions were needed before sowing winter wheat, because of

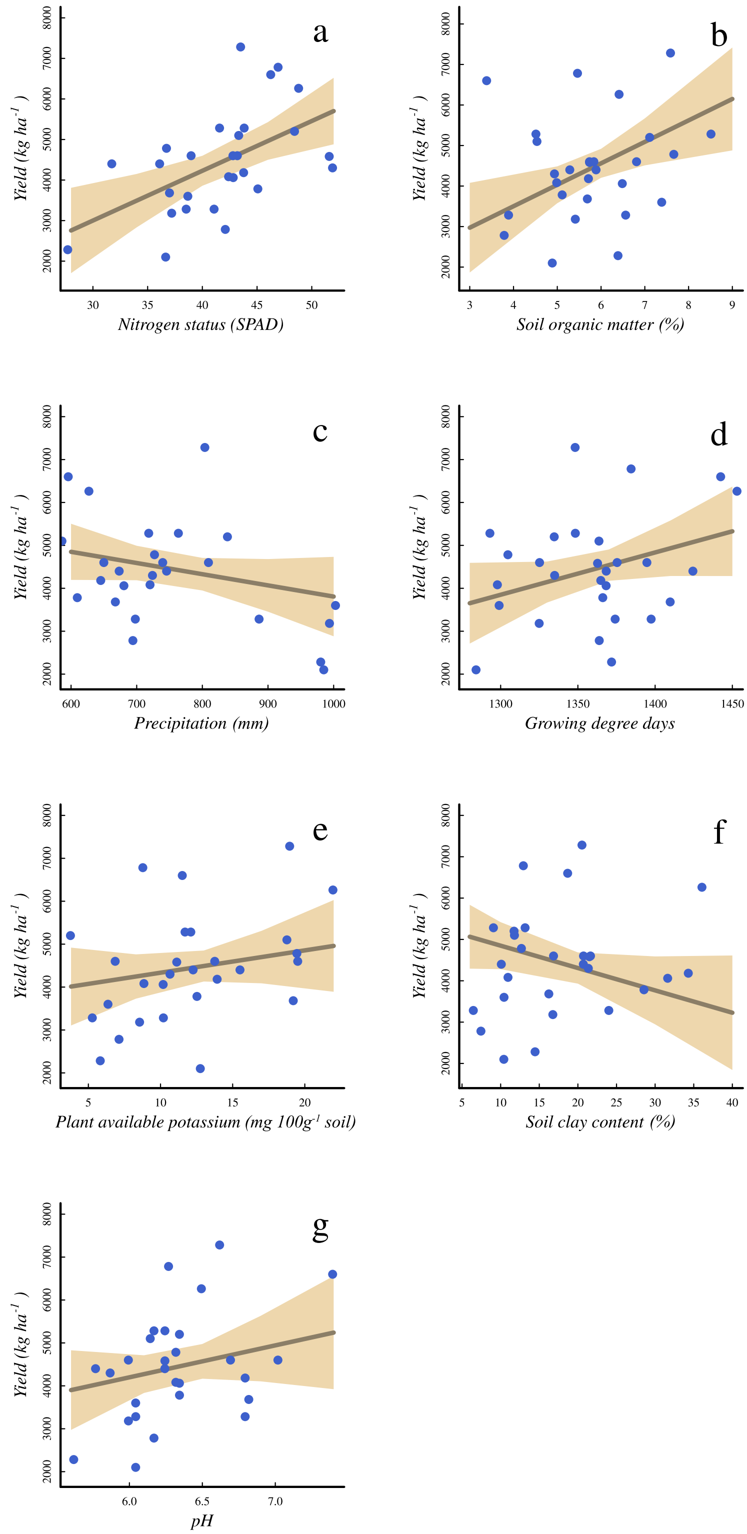


Fig. 5. Data and model effects of mediators of winter wheat grain yield: (a) nitrogen status, (b) soil organic matter, (c) precipitation, (d) growing degree days, (e) plant-available potassium, (f) soil clay content, and (g) soil pH. The line and shading shows effects and 95% confidence interval for the averaged linear model, with raw data shown as dots.

higher weed abundance in annual crop-dominated rotations (Mahaut et al., 2019).

4.2. Yield-enhancing pathways in organic farming systems

We illustrate a multitude of variables limiting yields, both related to field management and farming conditions. This was also shown by Casagrande et al. (2009) and Nkurunziza et al. (2020), who found that a combination of agronomic factors affected crop performance and yield of organic cereals. However, with our approach we obtained a better understanding of how management affects yields through field states. Notably, some management options affected yields through multiple

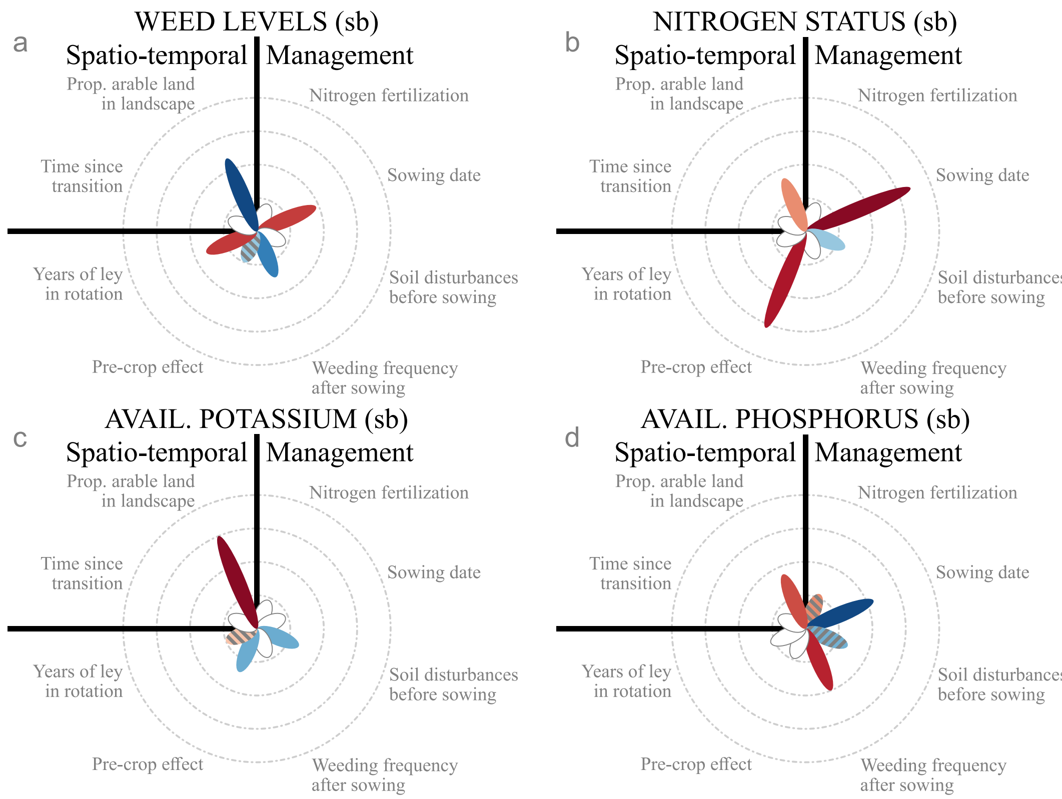


Fig. 6. Ranking of spring barley management and spatio-temporal context on (a) weed abundance, (b) nitrogen status, (c) plant-available potassium, and (d) plant-available phosphorus. For explanation of symbols and colours, see Fig. 3.

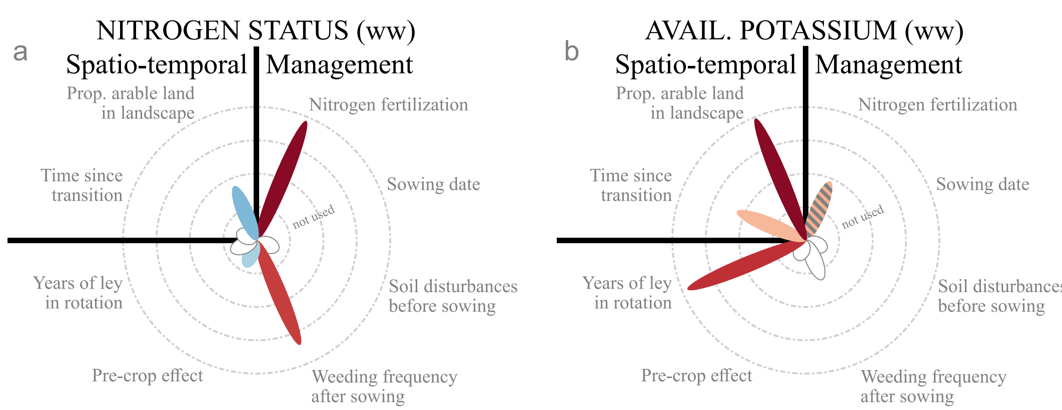


Fig. 7. Ranking of winter wheat management and spatio-temporal context on (a) nitrogen status and (b) plant-available potassium. For explanation of symbols and colours, see Fig. 3.

and interconnected pathways, illustrating how a combination of factors can improve organic yields. A first example of such pathway that we found strong connected weeding and nutrient management in winter wheat, where high weeding frequency combined with high nitrogen inputs increased yields via improved nitrogen status. As expected, we found nitrogen status to limit yields for winter wheat, but it was also mediated by mechanical weeding effects. Weed levels as such did not influence wheat yield but instead strongly affected plant-available nitrogen, illustrating the importance of considering nutrient mediation in weed-crop competition to improve crop yields (Little et al., 2021; Karlsson et al., 2025).

In spring barley, the pathways connecting nitrogen status and weed pressure with yield in spring barley were both influenced by sowing date. Late spring sowing for barley was associated with higher nitrogen status, which is consistent with Nkurunziza et al. (2020), suggesting that sowing date influenced spring barley yields. However, we also found that late sowing was associated with higher weed levels for spring barley, which can be explained by a lower competitive advantage of the crop over weeds when the crop establishes late (Nichols et al., 2015). This result therefore suggests a complex interplay between sowing date and barley yield as we found that late sowing was associated with both a negative and a positive mediator of barley yield.

In contrast, we found that the pre-crop contribution to barley yield was associated positively with nitrogen status, without significantly affecting weed levels, and thus seems like a promising pathway to efficiently increase nitrogen uptake of spring barley. Weed levels in spring barley were negatively associated with the proportion of arable land in the landscapes, which had a less strong effect on nitrogen status. Highly arable landscapes, have few refuges where diverse weed communities can be sustained, resulting in depleted seed banks due to low colonisation from surrounding non-crop habitats (José-María and Sans, 2011). Low weed pressure in arable contexts could also be the result of higher soil fertility compared to landscapes with more non-crop habitats (Persson et al., 2010), that can in turn benefit crops early after seed emergence and increase crop competitivity against weeds (Little et al., 2021). Our study therefore demonstrates the importance of considering the landscape and environmental context, in addition to agronomical factors, to understand the effect of weeds on crop yields.

In practical terms, this puts an emphasis of finding solutions to the problem of nutrient availability in organic farming, for example by increasing the circulation of nutrients from human waste or identifying novel sources of nutrients such as biogas digestate (Koppelmäki et al., 2019; Lee et al., 2021). Likewise, optimization of weed management, including the use of innovative techniques, is a key issue for organic farming (MacLaren et al., 2020).

4.3. Environmental mediators of yield-enhancing pathways

Another major result from our study is that by accounting for the complexity in cropping systems in organic farms, we could show that biophysical factors linked to the environmental context of farms was related to wheat and barley yields to the same extent as, and independently of, farming practices.

We found that the major environmental mediator of yields in both crops was soil organic matter content, which was positively related to winter wheat yield but negatively related to spring barley yield. This result may seem counterintuitive, but in our study, winter wheat fields aiming for higher quality (food or seed) were associated with practices favouring build-up of soil organic matter content (SOM), such as long-term leys in the crop rotation (Martin et al., 2020; Fig. S2, PC1 of winter wheat), this was not the case for spring barley fields. This contrast could also reflect spatial crop allocation by farmers based on their production targets (Thenail et al., 2009), such that winter wheat is grown primarily on the best fields, which are rich in SOM. As a cash crop, winter wheat is expected to be carefully managed to achieve high grain quality and quantity, and therefore the wheat fields in our study may to a larger extent represent the most yield-enhancing management practices possible (compare with Seufert et al., 2012). In contrast, spring barley fields may have been subjected to more diverse management practices compared to winter wheat, because of its greater range of intended uses (Fox et al., 2009) and comparatively less specific nitrogen requirements to meet quality standards for human consumption for spring barley (Bertholdsson, 1999). Our results contrast with Oelofse et al. (2015) which found that once N is controlled, the residual effects of SOM on spring barley yield were modest, especially in soils with very low clay (<5%). However, all our fields we investigated were above 5% of clay and were managed with less nutrient inputs, compared to the conventional field trials in Oelofse et al. (2015). Irrespective of the mechanisms involved in the effect of SOM on wheat and barley yield, our results demonstrate that regional variation in SOM correlates with yield, and that it should be considered as an important parameter to manage to improve organic cereal yields, in combination with weeding and fertilizing practices. The detailed relationships should be interpreted with caution and explored further in future studies.

A prioritisation for the best fields and best positions in the crop rotation for winter wheat might also explain why wheat yields were strongly affected by a more limited set of mediating factors, compared with spring barley. By allocating their most intensive crop rotations (containing winter wheat) to their most productive fields, the variation in environmental context of winter wheat fields might have been more restricted than for spring barley fields. Among these factors, we found that soil clay content and pH were important correlates of barley yield. High clay content generally benefits cereal yields (Valkama et al., 2016), but in the northern part of our two study regions, negative correlations have also been documented, probably explained by soils with high clay content having poor structure and/or being too wet and poorly aerated in the rooting zone (Fukumasu et al., 2022). In such conditions, farmers might avoid growing crops with a high-yield potential such as winter wheat on soils with high clay content. In a similar vein, crop allocation could explain the stronger association we found for spring barley yield compared to winter wheat regarding soil pH conditions. Farmers might avoid sowing spring barley on more acidic soils, especially since it is typically more sensitive to low pH than winter wheat (Holland et al., 2019).

Furthermore, the effect of precipitation differed between the two crops in terms of environmental mediators. Winter wheat yield was negatively affected by precipitation levels while this factor did not influence spring barley yield. This trend could be explained by the unusually high precipitation in autumn 2019 in Västra Götaland (northernly area) during the early development period of winter wheat, with 50% more precipitation during October–December compared to the 30-year average, while the southern region (Skåne and Halland) received normal precipitation levels (Swedish Meteorological and Hydrological Institute, 2024). As winter wheat is sensitive to waterlogging (Sjulgård et al., 2023), the weather data over the entire growing season suggests that winter wheat could have been subjected to an excess of rainfall (and waterlogging) during the autumn.

4.4. Study limitations

Although our study breaks new ground in how real-world yields or organic farms depend on environmental and management factors, it also has some limitations. Given the relatively small number of farms, we employed standard statistical methods that were well suited to the dataset, but this did limit the possibility to discern and suggest improvements to the farmers specific management. Nevertheless, the approach provided interpretable results and lay the groundwork for applying more advanced analyses with larger available datasets to better understand the variability of the results. Whereas our single-year study captured spatial variation in yields and management practices across farms during a year with normal weather conditions and yields, it for obvious reasons cannot contribute to the understanding of how yields are affected by between-year variation in weather and its interaction with environmental and management variables. Additionally, farmers may use variously risk-sensitive strategies to mitigate risks associated with extreme weather conditions or occasional pest outbreaks (Droste et al., 2020), that may affect the interpretation of a single-year study as ours. Farmers also adjust cultivar choice, crop sequences, fertilisation and tillage at short notice, depending on many complex variables including weather and associated soil conditions, weed and pest pressure. Our study did not explicitly account for crop cultivar effects, due to a limited set of replicates for each cultivar in this observational study. Moreover, the certified seed use is mandatory and the limited market availability constrains the possibility for farmers to acquire seeds with desired characteristics. Farmers take decisions based on market prices and other inputs, introducing further temporal variation in management between years. For example, the particular year studied here had such low incidence of pests and diseases that we could not account for them in the analyses. This calls for long-term studies, using the analytical techniques that were advanced in this study, to fully understand what drives variation on organic yields. Observational studies show significant between-farm variation in productivity and adaptive capacity of the system in time, highlighting the need for tailored management strategies (Reidsma et al., 2007). In this context, broader analyses of nutrient use and climate impacts emphasize the importance of adapting practices to local and temporal conditions (Yan et al., 2022; Farooq et al., 2023).

This study focused on drivers of organic yields, but increased organic yields may also erode biodiversity and increase nutrient leaching and emissions (Gabriel et al., 2010; Röös et al., 2018; Sidemo-Holm et al., 2021). To mitigate trade-offs between crop production and the environment, future studies should include consideration of environmental effects of improving organic yields, where systemic approaches could be used to design cropping systems that are adapted to site-conditions (Lamine and Bellon, 2009) for example relying on permanent crop cover to reduce nutrient losses caused by soil erosion or leaching (Poeplau and Don, 2015; Valkama et al., 2016). Such studies could preferably be hybrid studies that combine observations in commercial fields with experimental manipulation of the commonly used management practices to determine pathways towards sustainable management.

5. Conclusion

By using a system approach, our study uniquely utilized a large diversity in organic farming practices of the economically important crops spring barley and winter wheat, to identify interlinked factors that limits yields, thus identifying multiple pathways to mitigate such limitations. Our results suggest that key management levers for farmers include combined management of nitrogen, mechanical weeding, and sowing timing to optimize cereal yields. For winter wheat, fields with good nitrogen status were associated with high nitrogen inputs and high mechanical weeding frequency. For spring barley, both late sowing date and appropriate pre-crop were linked with good nitrogen status, but later sowing date was also related to increased weed problems. The identification of these potentials for improved organic cereal yields was made possible by utilising the rich diversity of management practices across commercial farms. We emphasize important patterns in management practices, such as how the intended use of the crop can shape weeding effort but also be associated with discrepant management strategies between the two crops; where spring barley and winter wheat were implemented in contrasting crop rotations when aimed at food or seed. However, some limiting factors for yields on these commercial farms were not under the short-term control of farmers, like low soil organic matter content or high precipitation for winter wheat, and high clay content and low pH for spring barley.

To develop and improve organic farming systems further, we suggest that there is a need for studies that capitalize on this extensive variation of management methods and their combinations on real farm and farming conditions, combining detailed quantification with a holistic approach. As we have shown, this enables emphasis of best practices within organic systems and offer valuable insights into practical and context-specific solutions to address challenges across different farming contexts. In this way, research can capitalize on farmer methodological innovations, to identify successful management practices, and help to establish benchmarking for more competitive organic yields. Our identification of yield limitation also calls for innovations to overcome these, but these may be challenging to implement from a technical, organizational and economic perspective. Further studies should therefore focus on actionable solutions to lift these constraints while addressing the sustainable dimension of the intensification of organic production.

CRediT authorship contribution statement

Rafaelle Reumaux: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Melanie Karlsson:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Romain Carrié:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Ingrid Öborn:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Christine A. Watson:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Göran Bergkvist:** Writing – review & editing, Supervision, Methodology, Conceptualization. **A. Sigrun Dahlin:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Johan Ekroos:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Johanna Wetterlind:** Writing – review & editing, Supervision, Resources, Methodology, Conceptualization. **Henrik G. Smith:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, 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.

Acknowledgements

This work was supported by the Swedish Research Council for Sustainable Development Formas [grant number 2018–02396]. We gratefully acknowledge the farmers of Västra Götaland, Skåne and Halland regions for being involved in the study and providing the data. We also thank Mark Brady for excellent input on early versions of the manuscript. The study was part of the BECC strategic research area at Lund and Gothenburg universities.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2026.104689.

Data availability

The data that was used for the analyses of this article are openly available at https://doi.org/10.5878/z95f-6h51.

References

Alvarez, R., 2022. Comparing productivity of organic and conventional farming systems: a quantitative review. Arch. Agron. Soil Sci. 68, 1947–1958. https://doi.org/10.1080/03650340.2021.1946040.

Andersson, E., Frostgård, G., Hjelm, E., Kvarmo, P., 2022. Rekommendationer för gödsling och kalkning 2023 [Recommendations for fertilisation and liming 2023], 15. Swedish Board of Agriculture. Jordbruksinformation, p. 2022. https://www2.jordbruksverket.se/download/18.4627c3ef191fdbf8ba3520f/1726670182663/jo23_17.pdf (In Swedish).

Arnold, T.W., 2010. Uninformative parameters and model selection using Akaike's information criterion. J. Wildl. Manag. 74, 1175–1178. https://doi.org/10.1111/j.1937-2817.2010.tb01236.x.

Barbieri, P., Pellerin, S., Seufert, V., Nesme, T., 2019. Changes in crop rotations would impact food production in an organically farmed world. Nat. Sustainability 2, 378–385. https://doi.org/10.1038/s41893-019-0259-5.

Barton, K., 2022. MuMIn: Multi-model inference. In: R package version 1.47.1.

Bell, A., Jones, K., Fairbrother, M., 2018. Understanding and misunderstanding group mean centering: a commentary on Kelley et al.'s dangerous practice. Qual. Quant. 52, 2031–2036. https://doi.org/10.1007/s11135-017-0593-5.

Bertholdsson, N.O., 1999. Characterization of malting barley cultivars with more or less stable grain protein content under varying environmental conditions. Eur. J. Agron. 10 (1), 1–8. https://doi.org/10.1016/S1161-0301(98)00043-4.

Burnham, K.P., Anderson, D.R., 2002. Model selection and multimodel inference: a practical information-theoretic approach. Springer, New York.

Callaway, M.B., 1992. A compendium of crop varietal tolerance to weeds. Am. J. Altern. Agric. 7, 169–180. https://doi.org/10.1017/S088918930000477X.

Carberry, P.S., Hochman, Z., McCown, R.L., Dalgliesh, N.P., Foale, M.A., Poulton, P.L., Hargreaves, J.N.G., Hargreaves, D.M.G., Cawthray, S., Hillcoat, N., Robertson, M.J., 2002. The FARMSCAPE approach to decision support: farmers', advisers', researchers' monitoring, simulation, communication and performance evaluation. Agric. Syst. 74, 141–177. https://doi.org/10.1016/S0308-521X(02)00025-2.

Casagrande, M., David, C., Valantin-Morison, M., Makowski, D., Jeuffroy, M.-H., 2009. Factors limiting the grain protein content of organic winter wheat in south-eastern France: a mixed-model approach. Agron. Sustain. Dev. 29, 565–574. https://doi.org/10.1051/agro/2009015.

Cock, J., Oberthür, T., Isaacs, C., Läderach, P.R., Palma, A., Carbonell, J., Victoria, J., Watts, G., Amaya, A., Collet, L., Lema, G., Anderson, E., 2011. Crop management based on field observations: Case studies in sugarcane and coffee. Agric. Syst. 104, 755–769. https://doi.org/10.1016/j.agsy.2011.07.001.

Connor, D.J., 2018. Organic agriculture and food security: A decade of unreason finally implodes. Field Crop Res. 225, 128–129. https://doi.org/10.1016/j.fcr.2018.06.008.

Cornes, R., van der Schrier, G., van den Besselaar, E.J.M., Jones, P.D., 2018. An ensemble version of the E-OBS temperature and precipitation dataset. J. Geophys. Res.-Atmos. 123. https://doi.org/10.1029/2017JD028200.

Cribari-Neto, F., Zeileis, A., 2010. Beta Regression in R. J. Stat. Softw. 34. https://doi.org/10.18637/jss.v034.i02.
Darnhofer, I., Schneeberger, W., Freyer, B., 2005. Converting or not converting to organic farming in Austria:Farmer types and their rationale. Agric. Hum. Values 22, 39–52. https://doi.org/10.1007/s10460-004-7229-9.
De La Cruz, V.Y., Tantriani, V., Cheng, W., Tawaraya, K., 2023. Yield gap between organic and conventional farming systems across climate types and sub-types: A meta-analysis. Agric. Syst. 211, 103732. https://doi.org/10.1016/j.agsy.2023.103732.
de Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. Agric. Syst. 108, 1–9. https://doi.org/10.1016/j.agsy.2011.12.004.
Döring, T.F., Neuhoff, D., 2021. Upper limits to sustainable organic wheat yields. Sci. Rep. 11 (1), 12729. https://doi.org/10.1038/s41598-021-91940-7.
Droste, N., May, W., Clough, Y., Börjesson, G., Brady, M., Hedlund, K., 2020. Soil carbon insures arable crop production against increasing adverse weather due to climate change. Environ. Res. Lett. 15 (12), 124034. https://doi.org/10.1088/1748-9326/abc5e3.
Egnér, H., Riehm, H., Domingo, W.R., 1960. Untersuchungen über die chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. II Chemische Extraktions-methoden zur Phosphor und Kaliumbestimmung. Kungl. Lantbruks högsk. Ann. 26, 199–215 (In German).
Eyhorn, F., Muller, A., Reganold, J.P., Frison, E., Herren, H.R., Luttikholt, L., Mueller, A., Sanders, J., Scialabba, N.E.-H., Seufert, V., Smith, P., 2019. Sustainability in global agriculture driven by organic farming. Nat. Sustainability 2 (4), 253–255. https://doi.org/10.1038/s41893-019-0266-6.
FAO, 2021. The State of Food and Agriculture 2021. FAO, United Nations, Rome. https://doi.org/10.4060/cb4476en, 182pp.
Farooq, A., Farooq, N., Akbar, H., Hassan, Z.U., Gheewala, S.H., 2023. A critical review of climate change impact at a global scale on cereal crop production. Agron 13, 162. https://doi.org/10.3390/agronomy13010162.
Ficiciyan, A., Loos, J., Sievers-Glotzbach, S., Tscharntke, T., 2018. More than yield: ecosystem services of traditional versus modern crop varieties revisited. Sustainability 10, 2834. https://doi.org/10.3390/su10082834.
Follett, R.H., Follett, R.F., Halvorson, A.D., 1992. Use of a chlorophyll meter to evaluate the nitrogen status of dryland winter wheat. Commun. Soil Sci. Plant Anal. 23, 687–697. https://doi.org/10.1080/00103629209368619.
Fox, J., Weisberg, S., 2019. An R companion to applied regression, third edition. Sage, Thousand Oaks (CA).
Fox, G., Kelly, A., Bowman, J., Inkerman, A., Poulsen, D., Henry, R., 2009. Is malting barley better feed for cattle than feed barley? J. Inst. Brew. 115, 95–104. https://doi.org/10.1002/j.2050-0416.2009.tb00352.x.
Fukumasu, J., Jarvis, N., Koestel, J., Kätterer, T., Larsbo, M., 2022. Relations between soil organic carbon content and the pore size distribution for an arable topsoil with large variations in soil properties. Eur. J. Soil Sci. 73, e13212. https://doi.org/10.1111/ejss.13212.
Gabriel, D., Sait, S.M., Hodgson, J.A., Schmutz, U., Kunin, W.E., Benton, T.G., 2010. Scale matters: the impact of organic farming on biodiversity at different spatial scales. Ecol. Lett. 13 (7), 858–869. https://doi.org/10.1111/j.1461-0248.2010.01481.x.
Galipaud, M., Gillingham, M.A.F., Dechaume-Moncharmont, F.-X., 2017. A farewell to the sum of Akaike weights: The benefits of alternative metrics for variable importance estimations in model selection. Methods Ecol. Evol. 8, 1668–1678. https://doi.org/10.1111/2041-210X.12835.
Giam, X., Olden, J.D., 2016. Quantifying variable importance in a multimodel inference framework. Methods Ecol. Evol. 7, 388–397. https://doi.org/10.1111/2041-210X.12492.
Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature. Science 307, 550–555. https://doi.org/10.1126/science.1106049.
Grueber, C.E., Nakagawa, S., Laws, R.J., Jamieson, I.G., 2011. Multimodel inference in ecology and evolution: challenges and solutions. J. Evol. Biol. 24, 699–711. https://doi.org/10.1111/j.1420-9101.2010.02210.x.
Hartig, F., 2022. DHARMa: Residual diagnostic for hierarchical (multi-level / mixed) regression models. R package version 0.4.6.
Holland, J.E., White, P.J., Glendining, M.J., Goulding, K.W.T., McGrath, S.P., 2019. Yield responses of arable crops to liming – an evaluation of relationships between yields and soil pH from a long-term liming experiment. Eur. J. Agron. 105, 176–188. https://doi.org/10.1016/j.eja.2019.02.016.
Howard, P.J.A., Howard, D.M., 1990. Use of organic carbon and loss-on-ignition to estimate soil organic matter in different soil types and horizons. Biol. Fertil. Soils 9, 306–310. https://doi.org/10.1007/BF00634106.
Jiménez, D., Dorado, H., Cock, J., Prager, S.D., Delerce, S., Grillon, A., Bejarano, M.A., Benavides, H., Jarvis, A., 2016. From observation to information: data-driven understanding of on farm yield variation. PLoS One 11, e0150015. https://doi.org/10.1371/journal.pone.0150015.
José-María, L., Sans, F.X., 2011. Weed seedbanks in arable fields: effects of management practices and surrounding landscape. Weed Res. 51, 631–640. https://doi.org/10.1111/j.1365-3180.2011.00872.x.
Karlsson, M., Carrié, R., Wetterlind, J., Bergkvist, G., Ekroos, J., Smith, H.G., 2025. Weed–crop competition under improved nutrient management reveals trade-off between yields and weed diversity in organic farming. Biol. Agric. Hortic. 41 (3), 201–220. https://doi.org/10.1080/01448765.2025.2505896.
Kirchmann, H., 2019. Why organic farming is not the way forward. Outlook Agric. 48, 22–27. https://doi.org/10.1177/0030727019831702.
Knapp, S., van der Heijden, M.G.A., 2018. A global meta-analysis of yield stability in organic and conservation agriculture. Nat. Commun. 9. https://doi.org/10.1038/s41467-018-05956-1.
Kniss, A.R., Savage, S.D., Jabbour, R., 2016. Commercial crop yields reveal strengths and weaknesses for organic agriculture in the United States. PLoS One 11, e0161673. https://doi.org/10.1371/journal.pone.0161673.
Koppelmäki, K., Parviainen, T., Virkkunen, E., Winquist, E., Schulte, R.P.O., Helenius, J., 2019. Ecological intensification by integrating biogas production into nutrient cycling: modeling the case of Agroecological Symbiosis. Agric. Syst. 170, 39–48.
Lacoste, M., Cook, S., McNee, M., Gale, D., Bellon-Maurel, V., Hall, A., 2022. On-farm experimentation to transform global agriculture. Nat. Food 3, 11–18. https://doi.org/10.1038/s43016-021-00424-4.
Lamine, C., Bellon, S., 2009. Conversion to organic farming: a multidimensional research object at the crossroads of agricultural and social sciences: A review. Agron. Sustain. Dev. 29, 97–112. https://doi.org/10.1051/agro:2008007.
Lancashire, P.D., Bleiholder, H., Boom, T.V.D., Langelüddeke, P., Stauss, R., Weber, E., Witzenberger, A., 1991. A uniform decimal code for growth stages of crops and weeds. Ann. Appl. Biol. 119 (3), 561–601. https://doi.org/10.1111/j.1744-7348.1991.tb04895.x.
Le Bail, M., Jeuffroy, M.-H., Bouchard, C., Barbottin, A., 2005. Is it possible to forecast the grain quality and yield of different varieties of winter wheat from Minolta SPAD meter measurements? Eur. J. Agron. 23, 379–391. https://doi.org/10.1016/j.eja.2005.02.003.
Lee, M.E., Steiman, M.W., Angelo, S.K.S., 2021. Biogas digestate as a renewable fertilizer: effects of digestate application on crop growth and nutrient composition. Renew. Agric. Food Syst. 36, 173–181. https://doi.org/10.1017/S1742170520000186.
Little, N.G., DiTommaso, A., Westbrook, A.S., Ketterings, Q.M., Mohler, C.L., 2021. Effects of fertility amendments on weed growth and weed–crop competition: a review. Weed Sci. 69, 132–146. https://doi.org/10.1017/wsc.2021.1.
MacLaren, C., Storkey, J., Menegat, A., Metcalfe, H., Dehnen-Schmutz, K., 2020. An ecological future for weed science to sustain crop production and the environment. A review. Agron. Sustain. Dev. 40, 24. https://doi.org/10.1007/s13593-020-00631-6.
Mahaut, L., Gaba, S., Fried, G., 2019. A functional diversity approach of crop sequences reveals that weed diversity and abundance show different responses to environmental variability. J. Appl. Ecol. 56 (6), 1400–1409. https://doi.org/10.1111/1365-2664.13389.
Martin, G., Durand, J.-L., Duru, M., Gastal, F., Julier, B., Litrico, I., Louarn, G., Médiène, S., Moreau, D., Valentin-Morison, M., Novak, S., Parnaudeau, V., Paschalidou, F., Vertès, F., Voisin, A.-S., Cellier, P., Jeuffroy, M.-H., 2020. Role of ley pastures in tomorrow's cropping systems: a review. Agron. Sustain. Dev. 40, 17. https://doi.org/10.1007/s13593-020-00620-9.
Meemken, E.-M., Qaim, M., 2018. Organic agriculture, food security, and the environment. Ann. Rev. Resour. Econ. 10, 39–63. https://doi.org/10.1146/annurev-resource-100517-023252.
Nakagawa, S., Freckleton, R.P., 2011. Model averaging, missing data and multiple imputation: a case study for behavioural ecology. Behav. Ecol. Sociobiol. 65, 103–116. https://doi.org/10.1007/s00265-010-1044-7.
Nichols, V., Verhulst, N., Cox, R., Govaerts, B., 2015. Weed dynamics and conservation agriculture principles: a review. Field Crop Res. 183, 56–68. https://doi.org/10.1016/j.fcr.2015.07.012.
Nkurunziza, L., Watson, C.A., Öborn, I., Smith, H.G., Bergkvist, G., Bengtsson, J., 2020. Socio-ecological factors determine crop performance in agricultural systems. Sci. Rep. 10, 4232. https://doi.org/10.1038/s41598-020-60927-1.
Oelofse, M., Markussen, B., Knudsen, L., Schelde, K., Olesen, J.E., Jensen, L.S., Bruun, S., 2015. Do soil organic carbon levels affect potential yields and nitrogen use efficiency? An analysis of winter wheat and spring barley field trials. Eur. J. Agron. 66, 62–73. https://doi.org/10.1016/j.eja.2015.02.009.
Persson, A.S., Olsson, O., Rundlöf, M., Smith, H.G., 2010. Land use intensity and landscape complexity—analysis of landscape characteristics in an agricultural region in Southern Sweden. Agric. Ecosyst. Environ. 136 (1), 169–176. https://doi.org/10.1016/j.agee.2009.12.018.
Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333, 1289–1291. https://doi.org/10.1126/science.1208742.
Piikki, K., Söderström, M., 2019. Digital soil mapping of arable land in Sweden – validation of performance at multiple scales. Geoderma 352, 342–350. https://doi.org/10.1016/j.geoderma.2017.10.049.
Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops – a meta-analysis. Agric. Ecosyst. Environ. 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024.
Ponisio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., Valpine, P., Kremen, C., 2015. Diversification practices reduce organic to conventional yield gap. Proc. R. Soc. B Biol. Sci. 282. https://doi.org/10.1098/rspb.2014.1396.
R Core Team, 2021. R: A language and environment for statistical computing, version 4.2.3 [Software]. R Foundation for Statistical Computing. https://www.R-project.org/.
Reganold, J.P., Wachter, J.M., 2016. Organic agriculture in the twenty-first century. Nat. Plants 2, 1–8. https://doi.org/10.1038/nplants.2015.221.
Reidsma, P., Ewert, F., Oude Lansink, A., 2007. Analysis of farm performance in Europe under different climatic and management conditions to improve understanding of adaptive capacity. Clim. Chang. 84, 403–422. https://doi.org/10.1007/s10584-007-9242-7.
Reumaux, R., Chopin, P., Bergkvist, G., Watson, C.A., Öborn, I., 2023. Land parcel identification system (LPIS) data allows identification of crop sequence patterns and diversity in organic and conventional farming systems. Eur. J. Agron. 149, 126916. https://doi.org/10.1016/j.eja.2023.126916.

Röös, E., Mie, A., Wivstad, M., Salomon, E., Johansson, B., Gunnarsson, S., Wallenbeck, A., Hoffmann, R., Nilsson, U., Sundberg, C., Watson, C.A., 2018. Risks and opportunities of increasing yields in organic farming - A review. Agron. Sustain. Dev. 38, 14. https://doi.org/10.1007/s13593-018-0489-3.
Roschewitz, I., Thies, C., Tscharntke, T., 2005. Are landscape complexity and farm specialisation related to land-use intensity of annual crop fields? Agric. Ecosyst. Environ. 105, 87–99.
Rundlöf, M., Smith, H.G., 2006. The effect of organic farming on butterfly diversity depends on landscape context. J. Appl. Ecol. 43, 1121–1127. https://doi.org/10.1111/j.1365-2664.2006.01233.x.
Sebillotte, M., Combe, L., Picard, D., 1990. Système de culture, un concept opératoire pour les agronomes. In: Les systèmes de culture. Inra, Versailles, pp. 165–196 (In French).
Seufert, V., Ramankutty, N., 2017. Many shades of gray—The context-dependent performance of organic agriculture. Sci. Adv. 3, e1602638. https://doi.org/10.1126/sciadv.1602638.
Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232. https://doi.org/10.1038/nature11069.
Sidemo-Holm, W., Carrié, R., Ekroos, J., Lindström, S.A., Smith, H.G., 2021. Reduced crop density increases floral resources to pollinators without affecting crop yield in organic and conventional fields. J. Appl. Ecol. 58 (7), 1421–1430. https://doi.org/10.1111/1365-2664.13887.
Sjulgård, H., Keller, T., Garland, G., Colombi, T., 2023. Relationships between weather and yield anomalies vary with crop type and latitude in Sweden. Agric. Syst. 211, 103757. https://doi.org/10.1016/j.agsy.2023.103757.
Smith, O.M., Cohen, A.L., Rieser, C.J., Davis, A.G., Taylor, J.M., Adesanya, A.W., Jones, M.S., Meier, A.R., Reganold, J.P., Orpet, R.J., Northfield, T.D., Crowder, D.W., 2019. Organic Farming Provides Reliable Environmental Benefits but Increases Variability in Crop Yields: A Global Meta-Analysis. Frontiers in Sustainable Food Systems 3. https://doi.org/10.3389/fsufs.2019.00082.
Smith, O.M., Cohen, A.L., Reganold, J.P., Jones, M.S., Orpet, R.J., Taylor, J.M., Thurman, J.H., Cornell, K.A., Olsson, R.L., Ge, Y., Kennedy, C.M., Crowder, D.W., 2020. Landscape context affects the sustainability of organic farming systems. PNAS 117, 2870–2878. https://doi.org/10.1073/pnas.1906909117.
Swedish Board of Agriculture, 2015. Föreskrifter om ändring I Statens jordbruksverks föreskrifter och allmänna råd (SJVFS 2004:62) om miljöhänsyn i jordbruket vad avser växtnäring. SJVFS 2015:21. https://lagen.nu/sjvfs/2015:21 (In Swedish).
Swedish Board of Agriculture, 2022. Ekologisk växtodling 2021 [Organic arable farming 2021]. Jordbruksverkets statistikrapporter, Report no. JO0114. Jordbruksverket. https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2022-05-17-ekologisk-vaxtodling-2021.
Swedish Environmental Protection Agency, 2018. Nationella Marktäckedata [National Land Use Data]. Naturvårdsverket. https://www.naturvardsverket.se/verktyg-och-tjanster/kartor-och-karttjanster/nationella-marktackedata/.
Swedish Institute for Standards, 2005. Standard - Soil quality - Determination of pH (ISO 10390:2005, IDT) SS-ISO 10390:2007 - Swedish Institute for Standards, SIS. Svenska institutet för standarder, SIS. https://www.sis.se/en/produkter/environment-health-protection-safety/soil-quality-pedology/chemical-characteristics-of-soils/ssiso103902007/.
Swedish Meteorological and Hydrological Institute, 2024. Månads-, årstids- och årskartor av nederbördsavvikelser. Link (ex: December). https://www.smhi.se/data/meteorologi/kartor/avvikelse/manadsnederbord-procent-av-normal-avvikelse/manad/december.
Thenail, C., Joannon, A., Capitaine, M., Souchère, V., Mignolet, C., Schermann, N., Baudry, J., 2009. The contribution of crop-rotation organization in farms to crop-mosaic patterning at local landscape scales. Agric. Ecosyst. Environ. 131 (3–4), 207–219. https://doi.org/10.1016/j.agee.2009.01.015.
Thorup-Kristensen, K., Dresbøll, D.B., Kristensen, H.L., 2012. Crop yield, root growth, and nutrient dynamics in a conventional and three organic cropping systems with different levels of external inputs and N re-cycling through fertility building crops. Eur. J. Agron. 37, 66–82. https://doi.org/10.1016/j.eja.2011.11.004.
Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C., Batáry, P., 2021. Beyond organic farming – harnessing biodiversity-friendly landscapes. Trends Ecol. Evol. 36, 919–930. https://doi.org/10.1016/j.tree.2021.06.010.
Tuomisto, H.L., Hodge, I.D., Riordan, P., Macdonald, D.W., 2012. Does organic farming reduce environmental impacts? – a meta-analysis of European research. J. Environ. Manag. 112, 309–320. https://doi.org/10.1016/j.jenvman.2012.08.018.
Valkama, E., Rankinen, K., Virkajarvi, P., Salo, T., Kapuinen, P., Turtola, E., 2016. Nitrogen fertilization of grass leys: yield production and risk of N leaching. Agric. Ecosyst. Environ. 230, 341–352. https://doi.org/10.1016/j.agee.2016.05.022.
Yan, X., Xia, L., Ti, C., 2022. Temporal and spatial variations in nitrogen use efficiency of crop production in China. Environ. Pollut. 293, 118496. https://doi.org/10.1016/j.envpol.2021.118496.
Yanagida, T., 2023. misty: Miscellaneous functions 'T. Yanagida'. R package version 0.4.7.