Developing organic farming

Agroecological challenges for sustainable intensification

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Melanie Karlsson

LUND UNIVERSITY

DOCTORAL DISSERTATION

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Abstract: One of the most important challenges for modern society is how to feed the world in a sustainable manner. Agriculture is an essential part of food production, but at the same time it has many negative impacts on the environment, through for example pollution, nutrient leaching, and greenhouse gas emissions, and it is a big driver of biodiversity loss. Organic farming is a farming system that in many ways reduces these negative effects, however, it has lower yields and therefore its sustainability has been debated. Often neglected in this discourse is the possibility of raising organic yields without aggravating environmental impacts, thus improving its overall sustainability. Farmland biodiversity may play an important role in this quest. Biodiversity is on the one hand threatened by intensive agriculture but may at the same time benefit agriculture through the services it provides. Ecosystem services provided by farmland biodiversity include pollination of crops, pest control by natural enemies, and healthy soil providing efficient nutrient cycling. Weeds are generally considered a problem in farming because of competition with the crop leading to a potential yield loss, but they may also support a lot of beneficial organisms providing ecosystem services and contribute to a more diverse agroecosystem. With focus on mainly cereal crops in agriculturally productive areas of Sweden, where organic farming is currently rare, this thesis investigates how organic yields can be improved and if it can be done sustainably with special attention on the role of biodiversity. Combining field studies and experiments with farmer interviews and questionnaires, I show that organic farming is a diverse farming system, both regarding management and yields. The average yield of organic cereals is lower than conventional ones, however the yield difference is smaller when we account for the fact that organic farming is more common on less productive land. I identified several avenues to reduce the yield difference and improve organic yields, most importantly the nutrient management as the average fertilization was only half compared to in conventional fields. In practical terms, the extent that fertilization can be improved may be limited, because efficient organic fertilizers beyond manures are limited in supply and nitrogen-fixing crops such as legumes have a limited capacity to provide nutrients. I further show that improved nutrient management can have negative consequences for weed diversity and other biodiversity. Yields of organic cereals are also limited by competition from weeds in many cases, where weed pressure could be reduced by for example increased mechanical weeding. However, mechanical weeding is time and labour intensive for the farmer and weed removal may reduce the weed community's capacity to promote biodiversity. My results also demonstrate that weeds do not always cause a yield loss, and to alleviate the trade-off between yield loss and biodiversity benefits, weed management could focus on actions that favour the competitiveness of the crop, and diverse weed communities. This thesis demonstrates the tight relationship between organic farming and biodiversity, and how they sometimes counteract each other but also how they can support each other. Yields and the long-term sustainability of the organic farming system can be improved, but only if risks are carefully considered.

Key words: agriculture, organic farming, yield, sustainability, weeds, biodiversity, ecosystem services

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Till Farmor

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Abstract

One of the most important challenges for modern society is how to feed the world in a sustainable manner. Agriculture is an essential part of food production, but at the same time has many negative impacts on the environment, such as pollution, nutrient leaching, greenhouse gas emissions and is a big driver of biodiversity loss. Organic farming is a farming system that in many ways reduces these negative effects, however, organic farming has lower yields and therefore its sustainability has been debated. Often neglected in this discourse is the possibility of raising organic yields without aggravated environmental impact, thus improving its overall sustainability. Farmland biodiversity may play an important role in this quest. Biodiversity is on the one hand threatened by intensive agriculture but may at the same time benefit agriculture through the services it provides. Ecosystem services provided by farmland biodiversity include pollination of crops, pest control by natural enemies of the pests and healthy soil providing efficient nutrient cycling. Weeds are generally considered a problem in farming because of competition with the crop and potential subsequent yield loss, but they may also support a lot of beneficial organisms providing ecosystem services and contribute to a more diverse agroecosystem. With focus on mainly cereal crops in agriculturally productive areas of Sweden, where organic farming is currently rare, this thesis investigates how organic yields can be improved and if it can be done sustainably with special attention on the role of biodiversity. Combining field studies and experiments with interviews and questionnaires with farmers I show that organic farming is a diverse farming system, both regarding management and in yields. The average yield of organic cereals is lower than conventional ones, however the yield difference is smaller when we account for the fact that organic farming is more common on less productive land. I identified several avenues to reduce the yield difference and improve organic yields, most importantly the nutrient management as average fertilization was only half compared to conventional fields. In practical terms, the extent that fertilization can be improved may be limited, because efficient organic fertilizers beyond manures are limited in supply and nitrogen-fixing crops such as legumes have a limited capacity to provide nutrients. I further show that improved nutrient management can have negative consequences for weed diversity and other biodiversity. Yields of organic cereals are also limited by competition from weeds in many cases, where weed pressure could be reduced by for example increased mechanical weeding. However, mechanical weeding is time and labour intensive for the farmer and weed removal may reduce the weed community's capacity to

promote biodiversity, including ecosystem service providers. My results also demonstrate that weeds do not always cause a yield loss and to alleviate the trade-off between yield loss and biodiversity benefits, weed management could focus on actions that favour the competitiveness of the crop, and diverse weed communities. This thesis demonstrates the tight relationship between organic farming and biodiversity, and how they sometimes oppose each other but also how they can work together. Yields and the overall sustainability of the organic farming system can be improved, but only if opportunities are utilized and risks are carefully considered.

Populärvetenskaplig sammanfattning

Mat är en livsviktig del av våra liv, och därför så är det inte konstigt att jordbruk utgör en stor del av våra landskap. En viktig utmaning är således att se till att jordbrukets produktion är hållbar och kan förse oss med mat utan för stora konsekvenser för miljön och naturen. Utvecklingen av jordbruket det senaste århundradet har varit nyckeln till stor populationstillväxt, den ökade välfärden och samhällsutvecklingen. Men jordbruket har samtidigt stora konsekvenser för miljön, exempelvis så bidrar jordbruket till föroreningar, övergödning, utsläpp av växthusgaser och en stor förlust av biologisk mångfald. Den biologiska mångfalden påverkas av jordbruket på många sätt, både på grund av skötselåtgärder så som besprutning, intensiv jordbearbetning och gödsling, vilket förändrar vilka arter som trivs i jordbrukslandskapet. Men också indirekt då många av de mer eller mindre naturliga miljöerna i landskapet har försvunnit till förmån för jordbruksmark. Samtidigt är den biologiska mångfalden viktig att bevara, inte minst för att den kan bidra med många fördelar för oss och för jordbruket, de så kallade ekosystemtjänsterna. Det handlar till exempel om vilda bin som bidrar till pollinering av våra blommor och grödor, predatorer av bladlöss och andra skadedjur och organismer som bidrar till en aktiv och näringsrik jord. Så genom att gynna den biologiska mångfalden kan vi också gynna matproduktionen och bidra till hållbarare jordbruk där behovet av besprutning och gödsling kan minska.

Ekologisk odling är på flera sätt ett mer hållbart jordbruk som ofta minskar föroreningar, gynnar biologisk mångfald, bidrar till levande jordar och minskar näringsläckage. Men ekologisk odling har inte lika höga skördar och producerar inte lika mycket mat på samma yta som de konventionella odlingsformerna, och det ifrågasätts därför ofta hur väl ekologisk odling kan fungera på större skala. En viktig fråga är därför om de ekologiska skördarna skulle kunna ökas samtidigt som fördelarna för miljön bibehålls och därmed bli ännu mera hållbar. Min avhandling undersöker hur den ekologiska odlingen fungerar i Sverige, vad som begränsar de ekologiska skördarna och hur de kan ökas. Jag undersöker också vilka möjligheter och problem detta skulle kunna innebära för den biologiska mångfalden. Avhandlingen inriktar sig på växtproduktion, till exempel odling av vete och korn, och fokuserar på de områden där jordbruket är som störst och mest intensivt i Sverige. Dessa områden är extra intressanta eftersom mängden ekologisk odling ofta är liten, men samtidigt så är potentialen för höga skördar stor och de positiva effekterna av ekologisk odling skulle kunna vara som störst.

I min avhandling visar jag att ekologiska skördar i genomsnitt är lägre än de konventionella, men att skördeskillnaden samtidigt är mindre än tidigare trott. Ekologiska fält finns oftare på mindre produktiva marker jämfört med konventionella och om man tar hänsyn till detta så minskar den genomsnittliga skördeskillnaden. Detta är ett viktigt resultat då jämförelser av den långsiktiga hållbarheten mellan ekologisk och konventionell odling baseras på deras respektive produktivitet. Jag visar också att det är en stor variation i skördar inom ekologisk odling, vilket tyder på stor potential att öka skördarna på många ekologiska fält.

De viktigaste faktorerna som bestämmer ekologiska skördar är näringstillförseln, ogräsproblem och odlingsförhållanden. Näringstillförseln är en väldigt viktig aspekt för skördar. Konventionella vetefält gödslas i genomsnitt dubbelt så mycket som ekologiska, det är därför inte konstigt att de ekologiska skördarna är lägre. För att höja näringstillförseln till ekologiska fält behövs en ökad tillgång på ekologiska gödslingsmedel och en ökad odling av grödor som bidrar med kvävefixering. Men att öka näringstillförseln kan också få stora konsekvenser för hållbarheten, eftersom det kan leda till ökad näringsförlust, övergödning och utsläpp av växthusgaser. Jag visar också att förbättrad näringstillförsel kan bidra till förlust av biologisk mångfald av ogräs när fälten blir mer näringsrika, vilket förändrar vilka ogräsarter som trivs.

Ekologiska skördar är också begränsade av mängden ogräs som konkurrerar med grödan om näring, ljus, plats och vatten. Det kan därför ses som självklart att mängden ogräs behöver minskas genom ökad ogräsbekämpning, men detta är inte nödvändigtvis det mest hållbara. Ogräs bidrar mycket till den biologiska mångfalden i jordbrukslandskapet så att ta bort dem helt är kanske inte önskvärt. Ett mer hållbart alternativ för att minska problemet är att försöka se till att grödan är konkurrenskraftig genom anpassad skötsel och val av sorter. Ogräsen skulle då inte göra lika mycket skada för grödan utan istället kan bidra till den biologiska mångfalden. Ogräs kan till exempel bidra med blommor, som gynnar pollinerande blomflugor.

Sammanfattningsvis, så är ekologisk odling en varierad odlingsform som har stor potential att öka sina skördar. Men om det ska göras, och hur, kräver noggrann genomgång av de risker, problem och möjligheter som uppstår, innan man kan utvärdera hållbarheten.

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Author’s contribution to the papers

Paper I

The study was planned and implemented by Melanie K and Rafaelle R, with support from the other authors. Melanie K did the data collection. Data analysis was shared between Melanie K and Romain C. The writing was mainly done by Melanie K, Romain C and Henrik S.

Paper II

All authors contributed to the planing and design of the study, led by Melanie K and Rafaelle R. Data collection was shared between Melanie K and Rafaelle R. Melanie and Rafaelle R jointly did the data analysis, with support from Romain C, Ingrid Ö and Henrik S. Melanie K and Rafaelle R developed the first version of the manuscript, which was further elaborated with the help of the full author group.

Paper III

Melanie K and the other authors, particularly Johanna W, planned and designed the study. All data was collected by Melanie K. Data analysis was done by Melanie K with support from mainly Romain C and Henrik S. The first draft was written by Melanie K, and further developed into a manuscript with the help of the other authors.

Paper IV

The planning and design of the study was done by Melanie K, with support from the other authors, based on an idea by Melanie K. The data collection was done by Melanie K. Data analysis was done by Melanie K with support from mainly Johan E. The writing was mainly done by Melanie K, Johan E and Henrik S.

Introduction

Environmental impact of agriculture

Agriculture is one of the cornerstones of modern society, where the agricultural intensification in the last century has enabled higher food production to sustain the growing population and societal development. The productivity of current agriculture is however at the cost of the environment, with biodiversity loss, eutrophication, soil degradation, pollution and greenhouse gas emissions as consequences (Foley et al., 2005). These detrimental effects of intensive agriculture result in the need for more sustainable farming strategies that minimize negative impacts on the environment whilst meeting the food demand, both today and in the future. The UN Sustainable Development Goals pinpoints these issues, with for example goal 2 stating that everyone should have access to adequate and nutritional food, goal 12 highlighting that any consumption and production should be sustainable, and goal 15 emphasizing the importance of protecting life on land and halting biodiversity loss (United Nations General Assembly, 2015).

One alternative farming strategy suggested to be more sustainable and environmentally friendly is organic farming. It is often associated with good soil quality, high soil organic matter and carbon sequestration, low pollution, low nutrient leaching and high biodiversity compared to conventional farming (Reganold & Wachter, 2016; Seufert & Ramankutty, 2017; Smith et al., 2019; Tuomisto et al., 2012). Many of these benefits arise from the lower intensity of organic farming, with the restrictions on the use of pesticides and mineral fertilizers. At the same time, this generally results in lower yields of organic crops, typically about 20-30% lower than conventional yields per hectare (de Ponti et al., 2012; Ponisio et al., 2015; Seufert et al., 2012). Because of the benefits with organic farming and the need for sustainable farming alternatives, the EU has set the goal to increase organic farming to 25% of the total arable land by 2030 (European Commission, 2020). In Sweden, which is the focus of this thesis, the goal is even more ambitious with 30% of the arable land aimed to be organically farmed by 2030 (Näringsdepartementet, 2019). The current share of organic farming in Sweden is 20% as of 2022 (Jordbruksverket, 2023a), and the share has been rather stable in the past years, which makes it unlikely that the goal will be met with the current trajectory.

The share of organic farming is not evenly distributed across Sweden (Fig 1), and it is particularly low in the most agriculturally productive areas of Sweden (Jordbruksverket, 2022b; Rundlöf & Smith, 2006). It may be extra important to study productivity of organic farming in these areas as the lower yields may be a contributing driver of the low adoption of the practice (Rundlöf & Smith, 2006; Smith et al., 2020). But also, these high-yielding areas are typically those where agriculture dominates the land-use and where farming is the most intense. This makes the relative ecological benefit of organic farming the highest in these areas (e.g. Smith et al., 2020; Tuck et al., 2014) and thus particularly important regions to focus on for studies regarding limitations to organic farming adoption.

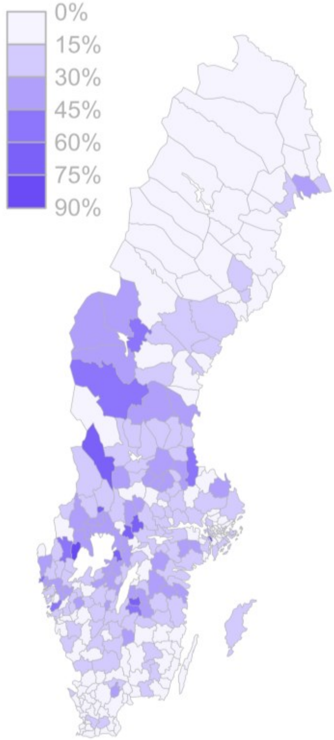

Figure 1 Map over the proportion of organically farmed land per municipality of Sweden in 2022 (calculated from Jordbruksverket, 2022a, 2022c, 2022d)

Organic farming - Sustainability and productivity

There are many environmental benefits with organic farming, yet it is often criticized, mainly for its lower yields (e.g. Kirchmann, 2019; Tscharntke et al., 2021). The magnitude of the yield difference depends on the crop, but also farming conditions such as location, soil and weather (Birkhofer et al., 2016; Seufert & Ramankutty, 2017; Smith et al., 2020), as well as nitrogen availability and weed problems (Alvarez, 2021; Seufert et al., 2012). Organic yields are typically also more varied than conventional, both spatially and temporally (Knapp & van der Heijden, 2018; Smith et al., 2019). Not only are yields (per hectare) typically lower with organic farming, but the total production per farm is also lower due to a higher need for manures and thus animal husbandry which requires a higher share of feed and non-food crops in the crop rotation (Alvarez, 2021). The critique concerning the lower yields and production with organic farming usually focuses on the presumed increase of land needed to produce the same amount of food with organic farming (Clark & Tilman, 2017; Green et al., 2005; Phalan et al., 2011). This in turn could have devastating effects for other land uses such as biodiversity conservation (Tscharntke et al., 2021).

Indeed, many environmental benefits with organic farming may decrease or even become negative when accounting for the lower yields, that is when the comparison are made per unit of output (for example kilogram of product) rather than per hectare of land being farmed (Clark & Tilman, 2017; Meemken & Qaim, 2018; Seufert & Ramankutty, 2017; Tuomisto et al., 2012). However, the debate rarely considers the potential for improving yields in organic farming. The large variation in organic yields suggests that there is a potential for raising them, but little attention has been given to this and the sustainability of doing so (Röös et al., 2018). This is what this thesis aims to do; study and discuss factors that constrain organic yields, and the effect that lifting these constraints may have on the environment, especially effects on biodiversity.

Agriculture and biodiversity

How agriculture impacts biodiversity

Many wild species live in or utilize the agricultural landscape, however, intensive agriculture and simplified landscapes are a large threat to farmland biodiversity (Emmerson et al., 2016). The most direct threat comes from pesticides which may affect both target and non-target organisms (Gaba et al., 2016; Geiger et al., 2010). Furthermore, the increased use of external fertilizer inputs has made farmland extremely nutrient rich where only certain species thrive, such as many problematic weeds, whilst more nitrophilous and sensitive species becomes increasingly rare (Rotches-Ribalta et al., 2015). Agricultural fields are also disturbed a lot by soil cultivation and tilling, which impacts the soil ecosystem drastically (Roger-Estrade et al., 2010) as well as weeds (Armengot et al., 2013) and some ground-dwelling organisms (Chmelik et al., 2019). In addition, the crops growing in the field alternate over time, with each crop having different characteristics of phenology, physical shape, life-history, and management regimes which makes the field suitable for different sets of wild species. Since different crops are suitable for different wild species, a high diversity of crops is desirable for supporting farmland biodiversity (Smith & Gross, 2007; Weisberger et al., 2019). However, in recent years arable landscapes have become increasingly specialised on growing just a few crops. For example, in the region of Skåne in southern Sweden, only 5 crops were grown on 78% of the farmed arable land in 2023 (Jordbruksverket, 2023b). Many agricultural landscapes are not only uniform in the crops that are grown, but they are also scarce in semi-natural landscape elements, such as field margins, due to the agricultural expansion. These semi-natural habitats are, however, important habitats and refuges for many species living in the agricultural landscape (Holland et al., 2017; Jeanneret et al., 2021).

How biodiversity impacts agriculture

The arable ecosystems and species within may impact crop production both positively and negatively, which is often called ecosystem services and disservices (Zhang et al., 2007). An example of an ecosystem service is natural pest control, where wild predators and parasitoids help regulate pest abundance and thus reduce crop damage. Specific examples of natural pest control include parasitoids of aphids, herbivores of weeds and weed seed predators. Pollination is another important service, as 75% of the worlds' crops benefit from animal or insect pollination (Klein et al., 2007), such as oilseed rape and fruits. Another ecosystem service is soil fertility and nutrient cycling, which is provided by a healthy soil ecosystem. Soils with a diverse and active biota not only help mineralize nutrients to make them available for the crop, but also prevent nutrient leaching and store carbon (Bender et al., 2016). Weeds are particularly important for many of these processes and the arable biodiversity as they support higher trophic levels (Diehl et al., 2011; Duque-Trujillo et al., 2023; Marshall et al., 2003). Weeds do however also provide a disservice by competing with the crop, which potentially causes yield loss (Zhang et al., 2007). Some species may be more competitive and harmful than others, for example by being very efficient at capturing nutrients or water, or if they grow big and tall and shade the crop (Gaba et al., 2017). On the other hand, many weed species do not interfere much with the crop and weed diversity may instead be favourable as more diverse weed communities have been shown to result in smaller yield losses than less diverse weed communities (Adeux et al., 2019; Storkey & Neve, 2018).

Agriculture and biodiversity in arable landscapes are clearly tightly linked, both through trade-offs and through synergies. Farmland biodiversity is thus a key component in the quest for more sustainable agriculture (Bommarco et al., 2013). Organic farming may play an important role in driving the transition to more sustainable farming (Eyhorn et al., 2019), especially considering its positive impact on biodiversity (Stein-Bachinger et al., 2021). Organic farming is not without its drawbacks, and it is important to consider if organic yields can be increased without compromising the environmental benefits, or if the environmental benefits can be increased without a reduction in yield (Foley et al., 2011; Röös et al., 2018; Wilbois & Schmidt, 2019).

Aims of the thesis

This thesis applies and integrates knowledge from both agronomy and ecology within the context of environmental science. I investigated the productivity and sustainability of organic arable farming, mainly cereals, in agriculturally productive regions of Sweden. In this quest I took advantage of the diversity of management practices in real organic farms to reveal the relationship between yield, management, and biodiversity for sustainable agriculture.

The thesis has two general goals. The first goal is to explore yield limitations of organic farming, through the two following aims:

> Aim 1: Investigate the importance of accounting for discrepancies in farming conditions and field management when studying the organic-conventional yield difference (paper I).
>
> Aim 2: In more detail, understand organic yield limitations, especially the relative importance of farming conditions and field management (paper II).

The second goal is to study how specific management practices impacts both yield and biodiversity, and mediate the interaction between the two:

> Aim 3: Study how fertilization and soil fertility simultaneously impact crop-weed competition, the weed community composition and diversity (paper III).
>
> Aim 4: Explore if diverse crop rotations may enhance weed diversity and ecosystem service providers as well as yields (paper IV).

Methods

Study designs

Four studies were designed for this thesis, with different aims, approaches, and crops in focus. Paper I was designed to understand the yield difference between organic and conventional farms, using a large-scale questionnaire study in southern Sweden (Fig. 2). Four common arable crops were included in the study: winter wheat, spring barley, oat and winter oil seed rape. All farms having previously grown any of these crops were identified. This study utilized a clustered design where organic farmers and their three closest conventional neighbours received the questionnaire via mail, asking about yields of the four crops and typical management practices. In total 4579 questionnaires were distributed, and answers were received from 1232. Data on farming conditions was based on available data from land-use maps (Naturvårdsverket, 2018), soil maps (Piikki & Söderström, 2019) and weather data came from the E-OBS database (Cornes et al., 2018). Some of these sources were also used in paper II and IV.

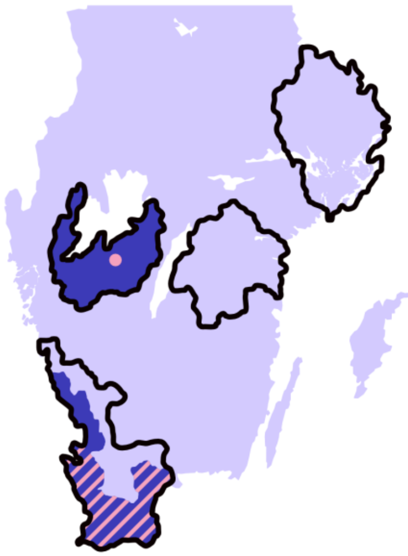

Figure 2 Map of the areas included in the four studies. Black outline: paper I, Dark blue: paper II, Pink dot: paper III, Pink hatching: paper IV

In paper II the organic management and yield limitations were investigated in more detail, using a field study complemented with farmer interviews about the field management to be able to understand yield limitations and the role of management. In this this study all established organic farms growing either or both spring barley and winter wheat in 2020 in the plains of the regions of Skåne, Halland and Västergötland were approached for participation (Fig 2), which led to 52 spring barley and 29 winter wheat fields being visited across the regions. These fields were visited to check crop growth, nitrogen uptake, weed and pest abundance.

Additionally, soil samples were gathered to estimate nutritional levels and other properties of the soil that may influence yields.

Having identified yield limitations in paper I and II, the thesis continued to the second general goal of evaluating how two of these yield influencing factors impact both yields and biodiversity; namely fertilization and crop rotation design. Fertilization poses a potential trade-off between yield and biodiversity due to increased competition from weeds and risks of altering the weed community composition. This was investigated in paper III using an experimental field study in a single field in Västergötland in 2022, where fertilization and weeding was manipulated in a randomized complete block design. Additionally, the study capitalized on the large differences in background soil nitrogen supply that the field harboured. This enabled to study the separate effect of the two sources of nutrients on weed-crop competition and potential loss of weed diversity and associated biodiversity.

Paper IV instead focused on a potential synergy between yield and biodiversity, namely if diversification of crop rotations may benefit both yields and biodiversity. Using an observational field study in spring barley fields in Skåne in 2021, we focused on fields with high crop rotation diversity, and conversely low amounts of ley in the rotation. All organic spring barley fields with rotations with between four and six different crop types, and only one or two years of ley in the past nine years of the crop sequence were identified using the IACS database which contains information on the crops grown in each field every year in Sweden. Four fields of each combination of crop rotation diversity and amount of ley were chosen such that the landscape heterogeneity (amount of semi-natural habitat) was maximized and not confounded with the diversity of the crop rotations. In these fields the weed community, hoverflies and ground dwelling insects were sampled, and the farmers were interviewed about the management practices of the fields.

Field data

In all three field studies, the weed abundance and/or weed community were surveyed. Weed abundance was measured as the total ground cover of the weed community, which is assumed to reflect the weed pressure and subsequent negative effect on yield. In paper III and IV, more emphasize was put on weed diversity and community composition, which meant that ground coverage was also estimated for each species separately. The diversity metrices of weed species richness and weed species evenness were calculated based on the weed surveys. In addition, in paper III the functional trait composition of the weed community was investigated, using plant functional trait data related to competition from the TRY plant trait database (Kattge et al., 2020). The traits investigated related to different aspects of competitiveness in the weeds, and the mean trait value of each trait was calculated for the entire weed community.

Arable fields harbour more species than just plants, such as insects and arthropods, many of which benefit from the weed community (Marshall et al., 2003). This associated biodiversity was encompassed in paper III by estimating the value of the weed community from two indicators, the average number of non-plant species associated with the weeds and the average nectar production, which indicates a benefit for pollinators (Tyler et al., 2021). These indicators were averaged across the weed community weighted by each weed species relative ground coverage. In paper IV abundance of non-plant biodiversity was sampled in the fields, in two ways. The first method was sweep netting along transects, capturing hoverflies (Syrphidae) which were later counted in the lab. Hoverflies are beneficial in agroecosystems as pollinators of crops and wild plants, additionally, the larvae of the sub-group Syphinae are predators of aphids (Rodríguez-Gasol et al., 2020). Secondly, ground-dwelling arthropods were captured using pitfall traps, where spiders (Aranea) were counted and identified to genus. The spider abundance was further divided into two functional groups, web builders and cursorial species.

Farmer management practices

This thesis relies on natural variation in agricultural management practices to the study effects of management on yields and biodiversity. Therefore, interactions with farmers for information about their yield and management is a key part of the thesis. In paper I, a questionnaire was used to gather this data, the survey was possible to answer both digitally and on paper. The questions were mainly quantitative in nature, for example focusing on the farm's production system (organic or conventional), yields for 2019, estimated nitrogen input from fertilization, typical tilling strategy, frequency of weed control (both mechanical and herbicides for conventional farms) and pesticide application (only for the conventional farms). Similar data was obtained from the farmers in structured interviews in paper II and IV, but here questions were asked in more detail. For example, questions were added on types and amounts of different fertilizers used, frequency and type of soil cultivations and weeding practices, and the identity of the preceding crop and cultivar.

Statistical analyses

In paper I the yield per crop was analysed in relation to farming system (organic or conventional), farming conditions and management to determine their relative importance for the yield difference between the two farming systems. Further, interactions between farming system and management were investigated for a more detailed understanding of the results. And lastly, an in-depth investigation was done focusing on yield limitations within each farming system separately, to analyse the yield limitations and relative importance of them per farming system.

Paper II focused only on yields of organic farming and tried to determine drivers of the yield variation. The analyses first ranked the relative contribution of direct biophysical yield limitations, such as soil and weather conditions, nutrient availability and weed problems. Followed by analyses of how management practices may alleviate these yield limitations, and a description of management variation in organic farming.

Weed-crop competition was the focus of paper III, and the yield of wheat was analysed against the weeding and fertilization treatments and the soil nitrogen supply. This also included their interactions, to get a detailed understanding of the dynamics of weed-crop competition. For analyses of trade-offs with biodiversity, the effect of the two aspects of nutrient management on different aspects of the weed community (richness, evenness, abundance) and trait and indicator values was analysed.

Similar analyses were done for the weed community also in paper IV, but here analysing the effect of crop rotation diversity, landscape heterogeneity (amount of semi-natural habitat), and selected field management practices such as weeding and fertilization. The abundance of arthropods, separately for different groups, were analysed in relation to effects of the weed community and landscape heterogeneity. Finally, the potential direct and indirect effects of crop rotation diversity on yields were investigated using a piecewise structural equation model, with weed cover representing the indirect pathway.

All analyses in this thesis were done with linear regression models, or mixed linear regression models when it was needed to account for structured data, for example the block design in paper III and the repeated measures in paper IV. The models were usually fitted with gaussian structure but with some exceptions, for example weed cover was analysed with beta regression and some abundance data in paper IV were fitted assuming Poisson or negative binomial distributions. The models were either analysed in full or first simplified to reduce dimensionality due to limited sample size. The simplification involved stepwise elimination, except for the ranking of yield limitations in paper II which was based on model averaging using AIC. All analyses were done in the R software (R Core Team, 2023).

Results and discussion

In this thesis the diversity of management practices of organic cereals is showcased and utilized. Even though these fields are all farmed within the same set of organic rules, there is a large freedom of choice for farmers within these parameters. For example, we show that the farmers involved in the studies in this thesis use many different types and applications rates of fertilizers, different techniques for mechanical weed control, different soil cultivation strategies, choices of cultivars and crop sequence designs. Yields also vary considerably, with a three-to-six-fold difference, between the highest and lowest yields of the organic cereals in paper I and II. Similarly, conventional yields varied greatly between farms in paper I, with a six-to-ten-fold difference. It is important to understand the reasons of this variation and what determines the yields before we can evaluate opportunities to improve yields or sustainability.

Limitations to organic yields

I demonstrate in paper I and II that yields of both organic and conventional fields are influenced by the growing conditions, mainly weather and soil characteristics (Fig 3a and 4). This indicates that some yield variation is beyond the control of the farmer and that any management aiming at raising yields should consider adaptations to local farming conditions. Importantly, we showed that farming conditions impact the estimated yield difference between organic and conventional farming. Organic farming is more common in less favourable growing conditions (Fig 1) and accounting for this spatial pattern does reduce the yield difference (Fig 3a-b), especially in spring barley. Paper I further shows that the yield difference between organic and conventional farming is to a large extent driven by differences fertilization intensity. Controlling for differences in fertilization rate between organic and conventional farming reduced the expected yield differences, especially in spring barley (Fig 3a-b). Controlling for both biases (farming conditions and management intensity) between organic and conventional farming reduced the yield difference from 38 to 27 % in spring barley and from 39 to 27 % in winter wheat. These effects have not been specifically studied or quantified before (Meemken & Qaim, 2018), despite that unbiased comparisons of yields between organic and conventional farming should be vital when sustainability and productivity of the two systems are compared and evaluated. If biases are not accounted for, any large-scale comparisons between organic and conventional yields risk overestimating the actual production difference, which in turn may have consequences on how sustainable organic farming is perceived to be.

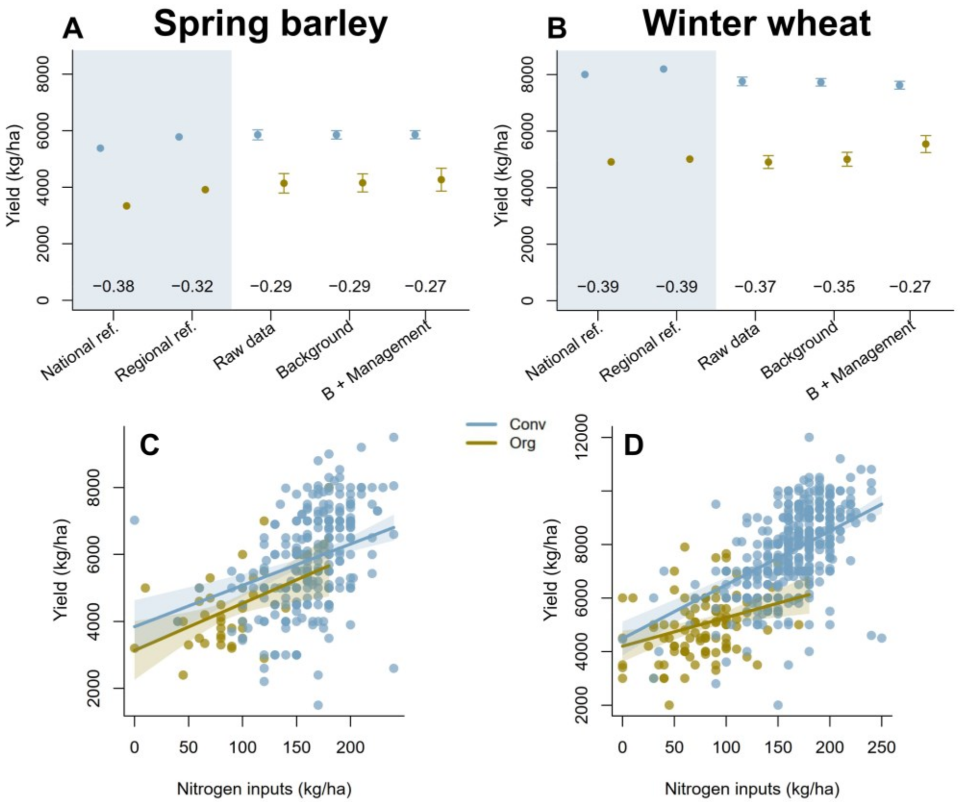

Figure 3 Estimated yield differences between organic (brown) and conventional farming (blue). (Top) as mediated by spatial differences in organic farming adoption and farming intensity, (a) shows spring barley and (b) winter wheat. The reference state is based on national statistics, to be compared with our raw data. Background controls for local farming conditions and B+mangement additionally accounts for difference in management such as nitrogen inputs. (Bottom) interactions between nitrogen input and farming system on yield with (c) spring barley and (d) winter wheat. Figures from paper I.

It is not surprising that the organic yields were lower, considering that the average nitrogen fertilization in organic winter wheat fields was only half compared to fertilization in conventional ones. But even at equal levels of fertilization in winter wheat, yields were not the same, probably due to additional factors limiting yields in organic farming (Fig 3c-d). Nitrogen availability has previously been pointed out as the main driver of lower organic yields (Fig 4; Seufert et al., 2012; Wilbois & Schmidt, 2019). This can mainly be explained by the low nitrogen contents of manures and restrictions on how much can be applied (Berry et al., 2002), and alternative (non-manure) fertilizers are scarce in supply (Case et al., 2017), which is another cause of the discrepancy in fertilization levels between the two farming systems. If the difference in fertilization levels between organic and conventional farming were smaller, then the yield difference would likely also be reduced. However, it is not only the amount of fertilization that is crucial but also the availability of the nutrient and timing relative to the crops demand, which is challenging in organic farming due to a slower release of nutrients from manures (Berry et al., 2002). Retaining the nutrients in the soil is important, which can be improved by the use of cover crops and catch crops (Kubota et al., 2018). Fertilizers are not the only source of nitrogen; legumes can be used to fix nitrogen from the air into the soil and additionally boosts nitrogen use efficiency and soil organic matter (Kubota et al., 2018; Stagnari et al., 2017). Paper III clearly shows the effect of soil nitrogen supply, separated from the effect of fertilization, demonstrating that such effects may be of the same magnitude of fertilization. Organic farms may be more prone to choosing a good preceding crop, especially for highly profitable crops such as wheat to try and maximize its potential (Reumaux et al., 2023).

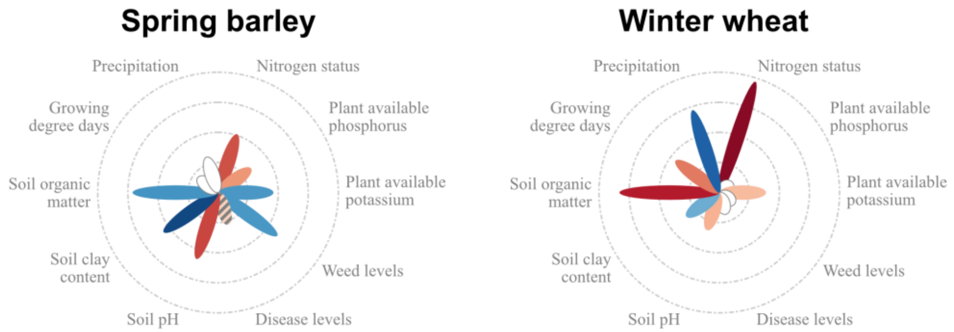

Figure 4 Yield limitations of organic farming for (a) spring barley and (b) winter wheat. The longer the petal the more important the factor is. Effects were negative (blue) or positive (red), with differences in the strength of the relationship indicated by intensity of colour. Grey hatching of petal indicates unsecure effects. Figures from paper II.

Beyond nutrient management, all papers show that weeds are an important yield constraint. In general, low weed levels and/or high frequency of weeding were associated with higher yields (e.g. Fig 4). High weed levels hinder crop growth through competition for limited resources: nutrients, light, water and/or space. The competition with weeds can be reduced by limiting weed levels through weeding, or by for example adapting sowing density, tilling strategy, or choice of crop variety to favour the crop (Blackshaw et al., 2000; Feledyn-Szewczyk & Jończyk, 2015; Kolb et al., 2010). Crop varieties are mainly breed for the conventional market with different priorities than organic (van Bueren et al., 2011) which means that traits favourable for high competitiveness such as quick crop establishment is not prioritized (Mason & Spaner, 2006). However, weeds are not always constraining yields and the effect may also be mediated by fertilization (Little et al., 2021), which was shown in paper III. In this experiment, only at one of the four fertilization rates the weeds caused a yield loss, despite relatively high weed levels. We explain this relationship by the relative competitiveness of the crop and weed community where the crop was advantaged by higher nutrient optimum (Wang et al., 2019) and superior in the competition for light being taller than the weeds. However, increased fertilization and soil nitrogen supply reduced weed community evenness in the experiment, and soil nitrogen favoured a more competitive weed community, which could elevate weed problems in the long-term. In contrast to weeds, we found very little problems with pests, such as aphids, and diseases in the studies, and no effect on yields from these factors (paper II, III and IV). Pests and diseases are currently rarely a problem in organic cereals, which is believed to be explained by the lower sap quality due to being less fertilized, which makes the crop less attractive and susceptible (Wraften et al., 2007).

Farmland biodiversity

In paper III we show that even though the weeds did not cause a yield loss at high fertilization, there was still a trade-off between yields and biodiversity conservation. Both increased fertilization and soil nitrogen supply had negative effects on weed diversity, specifically evenness of the weed community (Fig 5). Either the elevated nutrient levels (Rotches-Ribalta et al., 2015; Storkey et al., 2010), or increased competition from the crop (Pyšek & Lepš, 1991), caused shifts in the relative abundances of species within the weed community. We demonstrated that these shifts in weed community composition may further influence biodiversity. Increased soil fertility promoted a weed community that on average had more non-plant species associated with it, but produced less nectar.

In paper IV, we found no effect of diversifying the crop rotation on weed species richness or evenness (Fig 6). Our hypotheses rely on carry over effects between crops, but these effects may not be very strong. It is possible that effect is more apparent only when diversifying from simple to more complex rotation, but not diversifying already rather diverse rotations as in our study. Instead, it is possible that a better indicator of weed diversity changes would be weed diversity over all the crops in the crop sequence, since weed communities and weed diversity are typically very different between crops (Hofmeijer et al., 2021). We found that the number of flowering weed species decreased with high amounts of semi-natural habitat in the landscape. High numbers of flowering species were in turn positive for the abundance of hoverflies (Fig. 6). Hoverflies are important pollinators for other crops and plants, but for cereals they are mainly interesting since the larvae of some hoverfly species are predators of aphids and help regulate pest problems (Rodríguez-Gasol et al., 2020). However, the abundances of aphids were not very high in the study and did not relate to hoverfly abundance or yield.

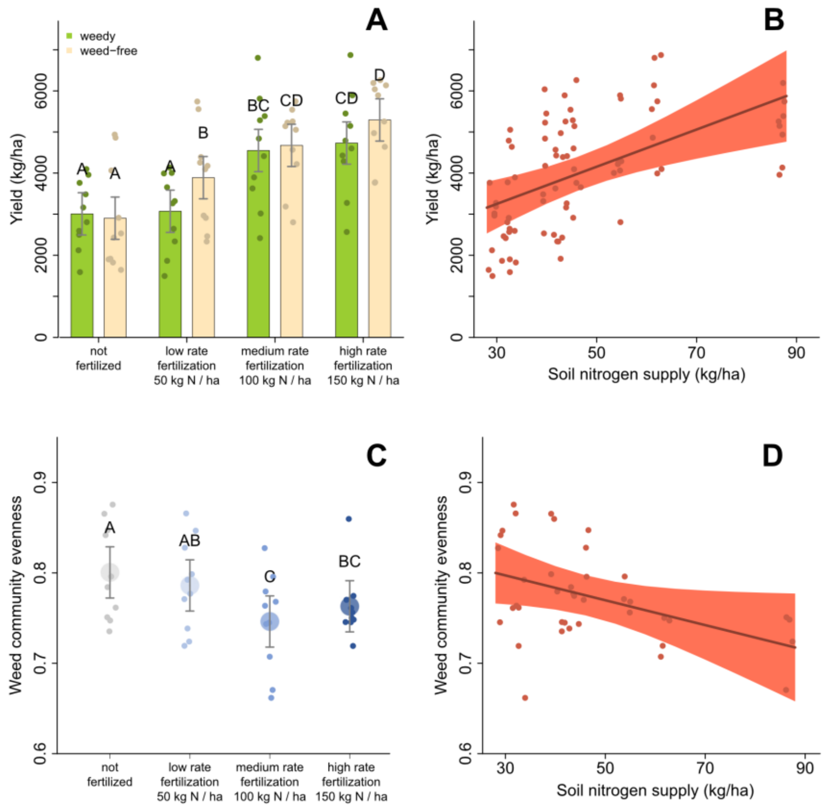

Figure 5 (Top) yield and (bottom) weed community evenness, impacted by fertilization rate and soil nitrogen supply. In the case of (a) in interaction between weeding and fertilization rate. Figures from paper III.

Local management of the field is not the only aspect that may influence arable biodiversity, but also landscape characteristics surrounding the arable fields play an important role. The heterogeneity of the landscape and specific landscape elements may be more important than management for determining weed species richness (Gabriel et al., 2005), since more simple and intensively managed agricultural landscapes host fewer weed species (Carmona et al., 2020). This was seen in paper IV where more simple landscapes had lower weed levels and a lower number of flower species. These effects are also more general across taxa which means that the benefit that organic farming provides for biodiversity is higher in simpler landscapes (Smith et al., 2020; Winqvist et al., 2012).

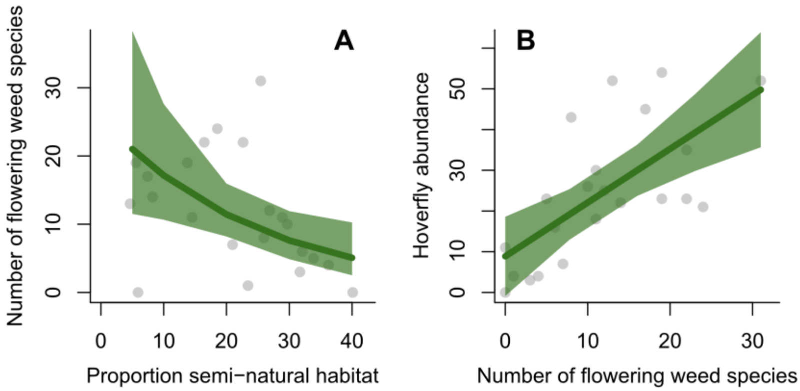

Figure 6 Relationship between (a) number of flowering weed species and semi-natural habitat, and (b) hoverfly abundance and number of flowering weed species. Figures from paper IV

Future of (organic) farming

In this thesis I show many avenues for how to raise organic yields, but one also need to understand the wider consequences of doing so to determine if these avenues promote sustainability. Nutrients was one of the main factors limiting yields, but improved nutrient management could induce problems. For example, it could lead to enhanced problems with weeds and pests, such as elevated competition with weeds because they become more abundant and/or more competitive. This was partly shown in paper III. With high levels of fertilization there is also an elevated risk for nutrient leaching (Kopke, 1995), especially with nitrogen from organic fertilizers and nitrogen fixating crops as it is difficult to match the availability of nutrients to the crops demand in time (Berry et al., 2002). With more nitrogen provided to the soil, greenhouse gas emissions in the form of nitrous oxide may increase (Hansen et al., 2019). Paper III also demonstrated a risk for shifts in weed communities and loss of weed diversity with increased nutrient supply, which may additionally negatively affect other biodiversity which benefits from the weeds. As already mentioned, there are many issues also with availability of fertilizers, in particular nitrogen, which is a large-scale constraint to organic farming (Barbieri et al., 2021). Increased supply of current alternative such as biogas digestate would increase fertilizer availability and improve the energy balance of the farm (Michel et al., 2010). It is especially beneficial if plant biomass is used as input for the digestion as it may further improve nutrient cycling in the crop rotation (Stinner et al., 2008). But more significant increases in nutrient availability may require changes in regulation to allow for new fertilizers, such as sewage sludge (Barbieri et al., 2021).

Improving yields through reducing the yield loss from weeds also has its concerns. Increased (mechanical) weed control could change the weed community composition (Fried et al., 2012). But mostly it would reduce weed abundance (paper II), which reduces the benefit for associated biodiversity and potentially reduce ecosystem service provisioning (Diehl et al., 2011). Mechanical weed control is also labour and time intensive for the farmers, and it would require fuel consumption. Previously the premise of improving the crops competitiveness was discussed to reduce the yield loss from weeds, but this may impact the weed community composition due to increased competition from the crop (Pyšek & Lepš, 1991). For long term sustainable weed management, focus should be on actions that favour diverse and non-detrimental weed communities that primarily provide services (Esposito et al., 2023; MacLaren et al., 2020). Given the benefits that weeds provide for ecosystem services, some yield loss could potentially be tolerated.

Other aspects important for sustainability beyond environmental impacts include for example profitability for the farmers and nutritional value of the products, where organic farming potentially exceed (Fess & Benedito, 2018). Organic farming is typically more profitable and not more costly for the farmer, but this may vary considerably due to markets and price premiums change (Smith et al., 2019). Economy is also a concern for consumers as organic produces are more costly, which does not make it accessible to everyone (Seufert & Ramankutty, 2017). Social benefits of organic farming for farmers and farm workers are not widely studied but show some evidence of being better (Reganold & Wachter, 2016; Seufert & Ramankutty, 2017). Further aspects for sustainability involves energy use efficiency which is higher of organic farming compared to conventional, both per unit of area and product (Lynch et al., 2011). Greenhouse gas emissions have also been shown to be lower in organic production systems per hectare, although the effect per product is uncertain (Lynch et al., 2011; Seufert & Ramankutty, 2017). These additional sustainability aspects should also be considered when the sustainability of farming practice or yields is evaluated.

Conclusions

In this thesis I have showcased the differences between organic and conventional farming and demonstrated the benefits of in-depth studies focusing on only organic farming. I also highlight the advantages of utilizing a varied set of approaches and combining field data with farmer interviews and questionnaires. I found that farming conditions have a large impact on yield and are important to account for when studying yield difference and yield limitations (paper I and II). I also show that there are many possibilities of improving yields through altered management, particularly nutrient and weed management. But the consequences of measures to do it need more attention, especially the observed trade-off between yield and many organism groups (Gabriel et al., 2013). Agriculture is inevitably linked to biodiversity in complex ways since biodiversity is threatened by agriculture but may also help making agriculture more sustainable through ecosystem services (Bommarco et al., 2013). I have in the thesis highlighted this problem, in paper III by demonstrating competitional dynamics and loss of biodiversity due to fertilization, and in paper III and IV by showing how weeds may contribute to ecosystem services that are relevant for agricultural production. But other risks with improved yields beyond biodiversity also need to be evaluated (Röös et al., 2018). Particularly trade-offs and synergies between different ecosystem services (Power, 2010), and potential trade-offs between different aspects of sustainability (German et al., 2017) would need further studies. Special attention should be given to study long-term effects in real production systems, especially in the light of climate change. There is also a need for studies on larger scales to look at the effect at whole farms or food systems (de Ponti et al., 2012).

The question of the role of organic farming in future sustainable farming still remains open. However, it is not only food production that is crucial, because currently it is estimated that 17% of the food produced globally is wasted (United Nations Environment Programme, 2021), and reducing food waste is important targets to fulfil the sustainable development goal number 12 (ensure sustainable consumption and production patterns; United Nations General Assembly, 2015). Large-scale change of diets to be more plant-based and reducing overconsumption could also enable more organic farming even though production is lower (Barbieri et al., 2021; Muller et al., 2017). There is evidence that the diets of consumers choosing organic produce are less meat based, however this does not fully compensate for the lower production of organic farming and there is still an elevated land use need (Treu et al., 2017). It may seem counterintuitive how plant-based diets could be compatible with organic farming given its dependencies on animal husbandry and manures. There are however increasing possibilities to produce organically without husbandry as non-manure based fertilizers are available, and legumes which are a big protein source in plant-based diets are nitrogen fixers and would contribute to fertilization (Stinner et al., 2008). Leys which are also a key part of organic farming for soil fertility, soil health and weed management could still be made profitable even if not used for fodder as it can for example be used as input in energy production (Koppelmäki et al., 2021).

Current land use, farming included, is not long term sustainable (Foley et al., 2005), and thus more sustainable practices needs to be implemented, where organic farming could help drive the transition (Eyhorn et al., 2019). To facilitate the conversion to more sustainable practices such as organic farming, and reaching the national goal of 30% organic farmland by 2030 in Sweden (Näringsdepartementet, 2019), there is a need for adequate demand for the products as well as fair profit and costs for the farmers (Karipidis & Karypidou, 2021; Sapbamrer & Thammachai, 2021). The willingness of farmers to adopt sustainable practices is further determined by their openness to change and environmental concerns, having sufficient knowledge before adoption and the risk perception (Dessart et al., 2019; Serebrennikov et al., 2020). There are problems but also avenues for organic farming becoming more sustainable, the trade-off between productivity and environmental benefits being one of them. Improving the yields and productivity of organic farming may be a way forward, but the ways in which it is done does require careful consideration to ensure that it actually improves, or at least not reduce, sustainability. The critical question we should ask is not whether current organic or conventional farming can feed the world, but their potential to improve and sustainably feed the world in the future.

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