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Comparison of the sustainability of ecological farming approaches using bio-economic modeling

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Abstract

EU and national policies foster ecological farming approaches to mitigate environmental pressures and increase sustainability of agricultural production. However, existing policies suffer from limited participation or low environmental benefits. To achieve the EU's ambitious sustainability targets, policy adoption and effectiveness need to increase. This dissertation assesses the sustainability of ecological farming approaches at farm-level and identifies the effects of policy and structural factors on performance levels and gaps.

The dissertation applies the bio-economic farm model FarmDyn to assess the economic and environmental impacts of two key policies affecting legume production in Europe. Findings indicate that while modest increases in legume production can be achieved with relatively low levels of Voluntary Coupled Support, more substantial changes require considerable subsidies. Allowing manure application to legumes under the EU Nitrates Directive can promote legume production while reducing the use of synthetic nitrogen fertilizers and imported protein-rich feeds, although the environmental benefits are limited.

Spatial and farm structural factors can considerably affect the performance and adoption of ecological approaches. This dissertation quantifies the economic effects of plot sizes and farm-plot distances based on big data on resource requirements of field operations and summarizes them in a regression model. The results reveal that the effects of plot sizes and farm-plot distances strongly impact the economic performance of ecological approaches, with stronger effects observed in conventional compared to organic farming systems. This suggests that potential profit gains from conversion to organic farming are higher for farms in more fragmented land structures.

The regression functions are implemented in the FarmDyn model to assess the economic potential of organic production for specialized arable farms cooperating with a biogas plant instead of taking up livestock production. The results show that organic farming exhibits high economic potential for specialized arable farms when the application of biogas digestate reduces the shortage of mobile nitrogen fertilizers. Stricter restrictions on its use reduce profitability and increase labor requirements.

This dissertation demonstrates that ecological farming approaches can have substantial economic potential. However, their economic performance is influenced by regulatory constraints from policies and private farming associations. Less stringent restrictions improve economic performance, but may compromise environmental benefits. Low adoption rates highlight the need for a balanced use of different policy instruments. The interaction of policy measures and goals requires that policies are considered in a broader context. This complexity makes the development of effective policies challenging, emphasizing the importance of detailed ex-ante analysis.

Zusammenfassung

Die EU und ihre Mitgliedstaaten fördern ökologische Bewirtschaftungskonzepte, um Umweltbelastungen landwirtschaftlicher Produktion zu verringern und ihre Nachhaltigkeit zu erhöhen. Um die Nachhaltigkeitsziele der EU zu erreichen, muss die Akzeptanz und die Effektivität bestehender Maßnahmen gesteigert werden. Diese Dissertation untersucht die Nachhaltigkeit ökologischer Bewirtschaftungskonzepte auf Betriebsebene und bewertet den Einfluss politischer und struktureller Faktoren auf ihre Wirtschaftlichkeit.

Das bioökonomische Betriebsmodell FarmDyn wird angewendet, um die wirtschaftlichen und ökologischen Auswirkungen von zwei politischen Maßnahmen auf den Leguminosenanbau in Europa zu bewerten. Die Ergebnisse zeigen, dass eine moderate Steigerung der Leguminosenproduktion mit geringen Fördermitteln möglich ist, während ein größerer Anstieg erhebliche Subventionen erfordert. Die Möglichkeit im Rahmen der EU-Nitratrichtlinie Gülle auf Leguminosen auszubringen kann ihren Anbau fördern und den Einsatz von Betriebsmitteln verringern, den ökologischen Nutzen jedoch auch eingrenzen.

Die Schlaggröße und die Entfernung eines Betriebes zum Schlag können die Leistung ökologischer Ansätze erheblich beeinflussen. In dieser Dissertation werden ihre wirtschaftlichen Effekte basierend auf dem Ressourcenbedarf von Feldarbeiten quantifiziert und in einem Regressionsmodell zusammengefasst. Die Ergebnisse zeigen, dass Schlaggrößen und -entfernungen einen erheblichen Einfluss auf ökonomische Indikatoren haben. Dieser Einfluss ist in konventionellen Produktionssystemen stärker ausgeprägt als in ökologischen. Dies deutet darauf hin, dass potenzielle wirtschaftliche Vorteile ökologischer Landwirtschaft in fragmentierten Landstrukturen größer sind.

Die Regressionsfunktionen werden in FarmDyn implementiert, um das wirtschaftliche Potenzial ökologischer Landwirtschaft für spezialisierte Ackerbaubetriebe zu bewerten. Anstatt in die Viehwirtschaft einzusteigen, wird dem Mangel an mobilen Stickstoffdüngern durch die Ausbringung von Gärresten entgegengewirkt. Die Ergebnisse weisen ökologischer Landwirtschaft ein hohes wirtschaftliches Potenzial aus. Strengere Beschränkungen des Einsatzes von Gärresten verringern die Rentabilität und erhöhen den Arbeitsaufwand.

Diese Dissertation verdeutlicht, dass ökologische Bewirtschaftungskonzepte ein erhebliches wirtschaftliches Potenzial haben können. Regulatorische Beschränkungen seitens der Politik und privater Landwirtschaftsverbände können die Wirtschaftlichkeit beeinflussen. Lockerere Auflagen können die Wirtschaftlichkeit erhöhen, aber den ökologischen Nutzen beeinträchtigen. Ein ausgewogener Einsatz verschiedener politischer Instrumente ist erforderlich um ihre Akzeptanz zu erhöhen. Die Wechselwirkung zwischen politischen Maßnahmen und Zielen erfordert eine umfassendere Betrachtung der Politik. Die Entwicklung wirksamer politischer Maßnahmen ist aufgrund dieser Komplexität eine Herausforderung und unterstreicht die Bedeutung detaillierter Ex-ante-Analysen.

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Abbreviations

BEFM	Bio-economic farm model
CAP	Common Agricultural Policy
CO_2	Carbon dioxide
COM	Various field crops combined
COP	Specialist cereals, oilseeds, protein crops
COP+R	Cereals, oilseeds, protein crops and root crops combined
EFA	Ecological focus area
eq	Equivalent
EU	European Union
FADN	Farm Accountancy Data Network
FSDN	Farm Sustainability Data Network
GHG	Greenhouse gas
GMO	Genetically modified organism
GWP	Global warming potential
KTBL	Kuratorium für Technik und Bauwesen in der Landwirtschaft
LHS	Latin hypercube sampling
N	Nitrogen
ND	Nitrates Directive
NRW	North Rhine-Westphalia
PDL	Pays de la Loire
RSMD	Root mean squared deviation
SCR	Soil climate region
UAA	Utilized agricultural area
VCS	Voluntary Coupled Support

Chapter 1

Introduction

Agricultural production is a major driver of climate change and environmental degradation as it is associated with negative environmental externalities, such as biodiversity and habitat loss, resource depletion and pollutant emissions (Springmann et al. 2018; IPES-Food 2019). At the same time, agricultural production itself depends on natural resources and processes, making agricultural productivity and resilience sensitive to environmental change (EEA 2023). Due to these linkages, unsustainable production systems that degrade the natural environment and its ecosystem services are considered one of the most serious threats to food security and safety (Bernard de Raymond et al. 2021; Buckwell et al. 2017). Mitigating environmental pressures and increasing the sustainability of agricultural production is therefore necessary to ensure the supply of safe, nutritious and healthy food and to protect productive agricultural land (EEA 2023).

Ecological farming approaches promise a solution to this problem, as they aim to reduce environmental impacts by conserving natural resources as well as ecosystems and their services. These approaches range from individual practices, including the avoidance of certain inputs (e.g., mineral fertilizers, pesticides), or diversification of crop rotation, to farming systems, such as organic farming.

The need to establish ecological approaches in agriculture is firmly established in European and national policies, where societal concerns towards environmental degradation and public health have led to a shift in policy agenda (Barnes et al. 2021; EEA 2022; Schebesta and Candel 2020). In the European Union (EU), for instance, the Common Agricultural Policy (CAP) and the European Green Deal with the accompanying Farm to Fork and Biodiversity Strategies aim to accelerate the transition to a sustainable food system by promoting the adoption of ecological approaches. The Farm to Fork Strategy seeks, for example, to reduce dependence on pesticides and excessive fertilization and to achieve at least 25% organic production on EU farmland by 2030. With the introduction of funding for eco-schemes, the new CAP further incentivizes the adoption of ecological approaches (EC 2020). In this context, and especially in the view of a growing world population, policy makers are challenged to find balanced trade-offs between (i) increasing sustainability and conserving the environment and (ii) ensuring food supply and safety in the agricultural sector (Vågsholm et al. 2020).

1.1 Motivation

Farmers have been using ecological approaches for several years, however, their adoption remains low (Latruffe et al. 2022). In the EU, slow progress has been observed, despite an increasing share of the CAP budget being devoted to environmentally friendly approaches over the last two decades (Barnes et al. 2021; Hasler et al. 2022). Several existing measures suffer from limited participation (e.g. Barnes et al. 2021; BMEL 2023; EC 2023) or low environmental effectiveness (e.g. Ait Sidhoum et al. 2023; Dupraz and Guyomard 2019; Feindt et al. 2021; DeBoe 2020; Hasler et al. 2022). The policy measures, thus, fail to achieve their goal of contributing sufficiently to the protection and conservation of the environment (UBA 2017; Pe'er et al. 2020). To achieve the ambitious targets of a more sustainable agriculture, the adoption and effectiveness of policies must be increased.

This requires a greater understanding of how to increase the attractiveness of ecological approaches to farmers as potential adopters (Latruffe et al. 2022). Farmer's decisions to adopt ecological approaches are complex and rely both on exogenous (e.g. agronomic conditions and economic context, policy framework, availability of inputs) and endogenous drivers which are related to the farm and the farmer's motivation (e.g. farm structure, age and education of farmers) (Barnes et al. 2021; Thompson et al. 2023). A large body of literature analyzes these drivers (Hansson et al. 2019; Sapbamrer and Thammachai 2021; Thompson et al. 2023), providing evidence that economic considerations are increasingly important and have considerable impact on the decision to adopt ecological approaches (Kleijn et al. 2019; Liu et al. 2018). Especially among recent and potential adopters of, for example, organic farming, financial reasons are gaining importance over non-economic concerns (e.g. Flaten et al. 2006; Koesling et al. 2008; Padel 2001).

To drive the adoption of ecological approaches at scale different knowledge gaps need to be filled. First, a stronger evidence base on the benefits and drawbacks that matter most to farmers, including farm-level profits and costs (Kleijn et al. 2019), should be established. Thereby, performance gaps, i.e., the differences in performance compared to a more conventional agriculture, are of particular interest. Second, increasing the knowledge on how the performance can be driven by structural and policy factors can help to better align policy and societal goals with farmers' needs. Finally, the potential contributions of ecological approaches to the different pillars of sustainability and their trade-offs are controversially discussed. Accordingly, in addition to the farmer's role as entrepreneur and their social aspects, the impacts of agricultural activities on societal and environmental concerns need further exploration. In particular, the potential tension between environmental sustainability and productivity objectives, which could reduce the likelihood that ecological approaches will be adopted, requires further analysis (Latruffe et al. 2022).

This knowledge is critical to drive adoption and increase the effectiveness of policies, however, the costs and benefits of ecological approaches are highly context-specific and largely depend on farm characteristics (e.g., Kleijn et al. 2019). Further, even when general recommendations are made, the farmers' adoption decisions may be hesitant because they are unsure whether the results of scientific studies are relevant to their specific farms and conditions (Kleijn et al. 2019). This stresses the need of in-depth analysis that account for farm heterogeneity.

The heterogeneity is especially prevailing in the northwest of Germany, which is one of the most diverse soil-climate regions in Germany (Roßberg et al. 2007). The region shows intensive production areas with high soil quality (high yield levels) and low shares of permanent grassland, regionally concentrated intensive livestock farming as well as low-productivity regions at higher altitudes with low shares of arable production (BGR; Thünen Institute 2022). At the same time, the adoption of ecological approaches is particularly low. The share of agricultural land in agri-environmental and climate measures is below the national average (BMEL 2021) and the share of organic farming in agricultural land is the lowest in Germany at less than 6% (Destatis 2021). Hence, studying ecological approaches in the northwest of Germany is of particular interest, as the political and societal goal of increasing the sustainability of agricultural production remains particularly ambitious.

1.2 Research aims

This dissertation, therefore, assesses the sustainability of ecological farming approaches at farm-level and identifies the effects of policy and structural factors on performance levels and gaps. It contributes to reveal barriers and opportunities for adoption of these approaches, including policy interactions and governmental challenges. Emphasis is placed on the economic performance, while also considering labor and environmental impacts and their trade-offs with economic outcomes. Given the circumstances and the low adoption rate of northwest Germany compared to the national average, the dissertation places its regional focus on this region.

To assess the potential impacts of ecological approaches and policy compliance strategies in at individual farm-level, this dissertation applies and extends a bio-economic farm model (BEFM). Using bio-economic optimization modeling in the context of this dissertation provides several advantages. First, BEFM allow for a detailed representation of farming activities and associated input-output relations with corresponding externalities (Janssen et al. 2010). Thus, BEFM explicitly consider interactions between production activities and can capture their implications for sustainable farm performance (Blanco 2016; Janssen and van Ittersum 2007). Second, BEFM are a useful tool for ex-ante analyses of the impact of changes in farming activities and policies on agricultural production, and related performance indicators (Janssen et al. 2010). Finally, farm-level analyses using BEFMs allow for capturing farm heterogeneity (Blanco 2016), which facilitates the identification of differential impacts of ecological approaches as well as their drivers. By incorporating a wide range of production activities, constraints and technologies, BEFM exhibit a high level of detail (Britz et al. 2021; Janssen and van Ittersum 2007) that allows for a profound representation of farm characteristics. In this context, the capability of using a sensitivity analysis allows to determine the effects of changes in underlying assumptions and uncertain parameters on model outcomes (Wossink and Renkema 1994).

In this dissertation, the bio-economic farm model FarmDyn is applied (Britz et al. 2023) which is a highly detailed single farm model. It provides a framework for simulating optimal farm-level plans and management decisions, and associated material flows and performance indicators under changing boundary conditions, including technologies and policy instruments (Britz et al. 2023). FarmDyn can be used to model a wide range of farming branches and activities, and its modular structure allows for the integration of extensions (Britz et al. 2021). Based on farm- and activity-specific differentiated data, the model provides a high level of detail regarding farm management. The associated high data requirements and the availability of a calibration approach that allows calibration to observed farm activities (Britz 2021) make the model particularly well suited for in-depth analysis of case studies (Britz et al. 2021; Britz et al. 2023).

FarmDyn is first applied to address the first research aim:

(1) Assess economic and environmental impacts of two key policy measures affecting legume production in Europe.

Increased legume production as one ecological approach can reduce negative externalities of agricultural production for example by substituting for protein-rich meals and fixing atmospheric nitrogen (N) (Peoples et al. 2009; Sasu-Boakye et al. 2014). In light of their environmental advantages and low crop share, EU member states can establish policies that foster their production, including Voluntary Coupled Support (VCS). On the other hand, the EU Nitrates Directive, with the aim of limiting nutrient pollutions from agriculture, may counteract legume production. This may especially apply if the national implementation of the directive restricts the N supply to legumes, thus potentially constraining their production on farms with high stocking densities. The implementation of the policies is very heterogeneous across member states, highlighting the need to identify their impacts on the farm performance. Differences in the policies across France and Germany, for example, may explain heterogeneous trends in legume production in recent years. While only France introduced VCS, the German implementation of the Nitrates Directive is more favorable for legumes as it allows the application of manure to legumes. FarmDyn is employed to assess the impact of the policies on the adoption of legumes and the economic and environmental farm performance, including, for example, greenhouse gas emissions, N leaching and the application of synthetic fertilizers. Further emphasis will be placed on the contribution of public payments to profitability as they are important instruments available to governments and private organizations to support the provision of environmental services (Latruffe et al. 2022). In particular, the interaction between the policy measures is addressed by simulating several scenarios with different implementations of these policies in a French and a German representative case-study farm. An in-depth sensitivity analysis of agronomic parameters reveals the impact of the policies as market settings shift.

In addition to market and policy factors, a variety of farm-related factors influence the performance and adoption of ecological approaches (Hansson et al. 2019). Besides farm management and family characteristics, these include spatial and farm structural factors (Hansson et al. 2019). While some factors, such as farm size and type, have been studied more frequently (Thompson et al. 2023), particularly with respect to the adoption of organic farming (Sapbamrer and Thammachai 2021), the effects of plot size and farm-plot distance have not yet been investigated. Due to major differences in crop production, the economic effects of plot sizes and farm-plot distances likely differ between conventional and organic farming systems and might thus affect the economic potential of conversion. Organic farming is one of the most frequently mentioned ecological approaches in EU policy documents (Latruffe et al. 2022), emphasizing the importance of in-depth analysis and knowledge of the drivers of performance and adoption. Hence, the second research objective is as follows:

(2) Quantify the effects of plot sizes and farm-plot distances on economic performance of organic and conventional farming.

A major problem in assessing the performance of ecological approaches is the lack of adequate and detailed data. This lack concerns both data on farms and their management with details on temporal and spatial resolution as well as on environmental monitoring (Reidsma et al. 2018). Large datasets that include both conventional and organic farms are scarce, and existing databases do not cover information on land fragmentation. Thus, econometric approaches that quantify the effects of plot-sizes and farm-plot distances for conventional and organic farming, and assess their impact on performance indicators are not applicable. To achieve the research aim, a structural analysis of a database on resource requirements of field operations covering organic and conventional production systems is conducted. The database contains information on field operations for more than one hundred crops in both conventional and organic production. A regression model is applied to derive for each crop labor and intermediate resource requirements that are associated with the use of machinery as a function of plot sizes and farm-plot distances. By applying the functions to case study farms of different farm type, the effects of plot sizes and farm-plot distances are quantified and their impact on the economic farm performance and performance gaps is assessed. The focus is set on costs of crop production and profitability, as well as labor requirements.

The regression functions are implemented to FarmDyn, where they allow for a consideration of the effects of plot sizes and farm-plot distances. Combined with the introduction of additional economic and agronomic data the model is extended to cover the wide range of crops under conventional and organic production. By doing so, this dissertation provides a comprehensive model extension that allows detailed comparisons between conventional and organic farming practices. This powerful tool is used for the analysis of the third research objective:

(3) Assess the economic potential of organic production for stockless arable farms importing biogas digestate under different regulations.

To be effective, organic farming needs to become mainstreamed. This requires that not only farms in specific contexts already open to conversion to adopt organic farming, but also standard farms (Latruffe et al. 2022). Increased adoption of organic farming by arable farms without taking up animal production appears to be key to driving conversion at scale. However, organic farms without livestock face a shortage of mobile N fertilizers. Biogas digestate offers a solution to this need for a flexible N fertilizer. Its use could support the conversion of specialized arable farms and, thus, contribute to the politically targeted expansion of organic production. Various regulations exist for the use of off-farm biogas digestate, which differ considerably in terms of the allowed import of N and thus could affect the economic performance. The bio-economic farm model FarmDyn is employed to assess the economic potential of organic production for three specialized arable farms without taking up animal production based on cooperation with a conventional biogas plant. The focus is on the impact of regulatory constraints imposed by policy and private farming associations, considering different regulations on the import of off-farm biogas digestate. By assessing several economic performance indicators under conventional and organic production and including a large-scale sensitivity analysis, the study provides valuable insights into the importance of the access to resources and farm structural characteristics, including distance to trading partners, and market and policy factors, such as subsidies and prices. Further emphasis is placed on the development of an N-balancing method that reflects the specificities of organic and conventional production. By implementing this method in the bio-economic model FarmDyn, it allows an in-depth analysis of organic farming and an improved comparison with conventional farming methods.

1.3 Proceedings

The dissertation is organized as follows: Chapter 2 evaluates the economic and environmental impacts of two major policies on legume production on a French and a German case study farm. In Chapter 3, a regression analysis is presented to quantify the effects of plot sizes and farm-plot distances on resource requirements in arable production, and to assess their effects on the economic performance of organic and conventional farming. The regression functions are implemented in FarmDyn. They are used to assess the economic potential of organic production for arable farms without livestock, based on the cooperation with a conventional biogas plant in Chapter 4. Chapter 5 concludes the dissertation.

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Chapter 2

Integrated assessment of legume production challenged by European policy interaction: A case-study approach from French and German dairy farms[1]

Abstract

Legumes, which currently show low production levels in the European Union, can reduce negative environmental externalities of agricultural systems by lowering nitrogen (N) fertilization and increasing protein self-sufficiency. This has led to the introduction of coupled support in France, in contrast to Germany. However, the German implementation of the Nitrates Directive is more favorable for legumes. Our study assesses economic and environmental impacts of these two policies affecting legume production. We employ the bio-economic model FarmDyn, representing French and German dairy farms. The results suggest that relatively low levels of coupled support can lead to modest increases in legume production, but that more substantial changes require considerable subsidies. Allowing the French farm to apply manure on legumes, as is already possible in Germany, fosters legume production while considerably reducing the use of synthetic N fertilizer and imported protein-rich feed. However, environmental benefits are limited.

Keywords

protein crops, mathematical programming, bio-economic model, leaching, global warming potential, nitrates directive

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2.1 Introduction

Increased legume production can reduce multiple negative externalities of agricultural production (Drinkwater et al. 1998). First, legumes can substitute for protein-rich meals as feed, which are often derived from imported crops and associated with the loss of natural habitats (Sasu-Boakye et al. 2014). Second, as legumes can fix atmospheric nitrogen (N), they need no, or limited, N fertilization and may even supply N to the soil, reducing N fertilization needs of the subsequent crop (Peoples et al. 2009). Thus, legumes provide both a marketable production of protein-rich feed (and food) and a partially non-marketable ecosystem service by providing N for subsequent crops (Wossink and Swinton 2007). By decreasing directly and indirectly the use of synthetic N fertilizer, legumes can reduce greenhouse gas (GHG) emissions (Jensen et al. 2012). In addition to the fixation of N, legumes can provide further ecosystem services (Zander et al. 2016). They regulate pests by breaking the cycle of weeds and diseases, leading to reduced pesticide application (Nemecek et al. 2008; Angus et al. 2015). After decades of a declining trend in their production, legumes, including forage legumes and soybeans, covered on average less than 4 per cent of the utilized agricultural area (UAA) between 2012 and 2017 in the European Union (EU) (Eurostat 2018). This largely reflects lower profitability compared to other major crops such as wheat and rapeseed, although several studies show that their inclusion in rotations does not decrease profits (Preissel et al. 2015). In addition, their use as feed generally cannot compete with substitutes such as imported soybean meal (Häusling 2011). At the scale of the European agro-food chain, legumes also suffer from a lock-in situation that tends to favor cereal and non-legume oilseed crops (Magrini et al. 2016), while sales of legumes face high transaction costs (Jouan et al. 2019).

Since 2014, in light of their environmental advantages and low crop share, European member states can establish voluntary coupled support (VCS) for legumes under Pillar I of the Common Agricultural Policy (CAP). Further, the cultivation of legumes can be acknowledged as a contribution to the requirement of the ecological focus area (EFA) as part of ‘Greening’. This helped to reverse the downward trend in legume production but heterogeneously across member states and regions, which mainly reflects differences in the implementation of the policy measures. For instance, both France and Germany count legume acreage with a factor of 1 for EFA, but only France introduced VCS[2] for legumes, reaching 145 million euros in 2017 (European Commission 2017). The VCS might explain why the French area of legumes nearly doubled between 2013 and 2017, reaching 3 per cent of UAA, but only increased by 35 per cent in Germany. Interestingly, the share of legumes in arable land in France is half as large in regions specialized in livestock production compared to regions specialized in arable crops (Eurostat 2018). This may be due to the French implementation of the Nitrates Directive (later called French ND) (91/676/CEE), which prohibits manure application on most legumes, discouraging their production on farms with high stocking densities (Caraes 2018). The German implementation of the Nitrates Directive (later called German ND) allows the application of manure on legumes as long as the mandatory N fertilization planning at farm scale is respected.

This study aims at assessing environmental and economic impacts of key policy measures affecting legume production in Europe: VCS for legumes and the national implementation of the ND. In particular, the interaction between these measures is addressed, since VCS aims at fostering legume production, whereas the ND can potentially constrain it by regulating N supply. We assess both the interaction and the effects of the policy measures by comparing in detail a French and a German representative case-study farm. Our first hypothesis is that VCS fosters legume production and protein self-sufficiency in both countries. Second, that implementing the German ND in France will lead to a further increase in legume production and protein self-sufficiency in France. Third, that these increases have positive environmental and economic implications at farm scale. We employ the bio-economic programming farm-scale model FarmDyn (Britz et al. 2014), to test these hypotheses and to quantify agronomic, economic, and environmental impacts.

So far, only a few studies have analyzed policies directly aimed at increasing legume production with farm-scale models (Helming et al. 2014; Cortignani et al. 2017). Studies using bio-economic models to analyze the ND and nitrate-related policies are more common (Peerlings and Polman 2008; Belhouchette et al. 2011; Kuhn et al. 2019). Nevertheless, as far as we know, there is no analysis that jointly considers several policies affecting legume production as we here compare such as here the measures under the first pillar of the CAP

[2] The French VCS budget supports five species and usages of legumes (grain legumes, forage legumes, soybeans, legumes for dehydration, and legumes for seed), each having its own sub-budget. While the VCS budgets are usually stable from year to year, the VCS per hectare varies with the acreage of each legume. Thus, the VCS per hectare is usually different between grain legumes (e.g. peas, faba beans) and dehydrated alfalfa. However, a minimum per hectare for possibility of fungibility is implemented. It guarantees that, if a part of the VCS budget for legumes is assigned to another farming sector (e.g. sheep), the VCS per hectare of legumes is a minimum of 100 € ha−1 (DGPE/SDPAC/2018-20).

and the implementation of the ND, thus providing an example of policy interaction (Nilsson et al. 2012). Besides, the impact of legume production has so far mainly been analyzed in arable cropping systems (Nemecek et al. 2008; Reckling et al. 2016), while fewer studies also consider their production on livestock farms for feed use (Gaudino et al. 2018; Jouan et al. 2020a). Finally, as far as we know, the study of Küpker et al. (2006) is the only one comparing in detail different farms in France and Germany, even though these countries are the main milk producers in the EU. Thus, our study addresses several gaps in the literature by (1) considering jointly multiple policies affecting legume production, (2) introducing legumes as cash crops and on-farm feed, highlighting the potential use of legumes to increase protein self-sufficiency, and (3) developing an integrated assessment of representative dairy farms in two European countries, France and Germany, whose regulations on legumes and manure management differ.

The paper is structured as follows: Section 2.2 describes two analyzed case studies, provides an overview of the model FarmDyn, and details how data related to legume production and the ND are introduced. Section 2.3 presents the results. Section 2.4 discusses policy implications and limitations of our approach, before a summary of the main conclusions.

2.2 Method

2.2.1 Overview of the FarmDyn model

Mathematical programming models represent a valuable tool to analyze technical changes or the introduction of (new) crops as they describe in detail farm management and investment decisions (Jacquet et al. 2011; Britz et al. 2012). Bio-economic models quantify both economic and environmental indicators and their trade-off by accounting for joint production of agricultural outputs and environmental externalities (Janssen and van Ittersum 2007). At farm scale, bio-economic models have the advantage of simulating in detail the decision-making process of the farmer, considering technical as well as work-time or financial constraints. This explains their frequent use in European policy impact assessments (Reidsma et al. 2018).

FarmDyn is a highly detailed bio-economic farm-scale model, building on mixed integer linear programming. It provides a framework for the simulation of economically optimal farm-level plans and management decisions, as well as related material flows and environmental indicators.

FarmDyn was applied by Lengers et al. (2013, 2014) to analyze GHG abatement measures in German dairy farming, by Kuhn et al. (2019, 2020) to assess impacts of the

German ND for multiple farm types at the level of a federal state, and by Schäfer et al. (2017) for the analysis of biogas production. Lengers et al. (2013, 2014) and Kuhn et al. (2019) combined large-scale sensitivity analysis with a meta-modeling approach, a methodology we follow here. FarmDyn maximizes the farm net present value under (1) the farms' production feasibility set, (2) working-time and (3) liquidity constraints, and (4) environmental and policy restrictions. By assuming a rational, fully informed, and risk-neutral farmer, the simulation results entail best-practice behavior. The extension of the linear programming with a mixed integer approach allows capturing indivisibilities, e.g. related to investments in stables and machines. The following section introduces elements of FarmDyn substantial for the underlying study; a complete documentation of FarmDyn is available online (Britz et al. 2019).

In our study, the comparative-static version of FarmDyn is used. The machinery pool used for the necessary field operation to grow legumes is already available, as it is also required to manage the observed benchmark crop rotation. Investment costs in buildings and machinery are annualized and herd dynamics are depicted by a steady-state model (i.e. the number of cows replaced in the current year is equal to the number of heifers raised for replacement).

Main indicators relate to the total farm profit, protein self-sufficiency (i.e. the ratio between protein produced to feed the herd and total protein consumed by the herd), and different environmental outcomes. The global warming potential (GWP) of the farm is calculated from emissions of different GHGs and expressed by their GWP relative to carbon dioxide. We provide a life-cycle perspective by covering on-farm emissions, for instance, of enteric methane or from fertilization and manure storage, as well as emissions from intermediate input use, such as from diesel or bought feeds. Since the ND aims to protect water quality by preventing nitrates polluting water bodies, we include an indicator for nitrogen leaching (later called N leaching). It calculates a probabilistic value for N leaching by considering different sources of N following the model SALCA-NO_3 (Richner et al. 2014).

2.2.2 Case studies and data implemented

We analyze as case studies one French and one German intensively managed dairy farm located in Pays de la Loire (PDL) in France and North Rhine-Westphalia (NRW) in Germany (Table 2.1). Intensive dairy farms were chosen as they combine salient features for the analysis: high quantities of manure produced per ha of land, such that restrictions on manure management from the ND are relevant; the possibility of using both grain and forage legume as feed; and compared to pig farms, more constrained feed choices linked to structural characteristics of the farm (e.g. part of fodder area). The case studies are defined based on longer time series data from agricultural institutions and extension services. The

French farm is based on the farm type ‘1b Pays de la Loire’ from Inosys Réseaux d'Elevage (IDELE 2016) as one of the most common types of dairy farms in that region. Detailed data are available for this farm type, such as crop rotation, stable inventory, and grass management. Besides, the crop rotation of this farm corresponds to the main crop rotation found in the PDL region (Jouy and Wissocq 2011). The German farm is based on farm type ‘Niederrhein NR_SB’ from Steinmann (2012), one of the most common types of dairy farms in NRW. Since no information on typical crop shares is provided by this source, related data are taken from Kuhn and Schäfer (2018), who derived typical crop rotations for different farm types in NRW based on data from agricultural census and expert interviews. For both farm types, yields are based on regional data and input and output prices on national data (mean 2013–7) (IFIP 2017; French Ministry of Agriculture 2018; AMI 2019; IT.NRW 2019; KTBL 2019). With a lower share of grassland and a higher stocking density, as well as higher crop and milk yields, the German farm is overall managed more intensively than the French farm (Table 2.1).

Table 2.1 Description of the dairy farms implemented in the FarmDyn model

	French farm	German farm
Arable land (ha)	49	60
Grassland (ha)	27	20
Number of dairy cows	62	75
Stocking rate (cow ha^{-1})	0.82	0.94
Breed	Holstein	Holstein
Milk yield (kg per cow per year)	8,600	8,800
Crops	Grassland, wheat, silage maize	Grassland, wheat, silage maize

In FarmDyn, each farm is calibrated by adjusting the working hours available on the farm, as well as the grazing periods for the herd and the energy content of grass. On the German farm, the yield of wheat is adjusted within a 5 per cent tolerance level. The dairy herd is kept fixed at benchmark levels in the analysis.

2.2.3 Introduction of legumes-related data

Three legumes are implemented to the FarmDyn model: peas, faba beans, and alfalfa (Table 2.2). Data on yields and on input and output prices for legumes and other crops are extracted from public statistics and professional agricultural press (IFIP 2017; French Ministry of Agriculture 2018; AMI 2019; IT.NRW 2019; KTBL 2019). German input prices for three legumes and concentrated feed are calculated by taking the buying prices for wheat and soybean meal as a basis to determine their value as animal feed, following the method available at DLR Westerwald Osteifel (2011). Peas and faba beans can be either used as feed or sold as cash crops, while alfalfa can only be used as feed. In the French region, a cooperative harvests and dehydrates alfalfa for its members (Leterme et al. 2019). It is assumed that this service could become available in Germany as well (Kamm et al. 2016). CO2eq emissions from the dehydration are considered in the model (Corson and Avadí 2016).

Table 2.2 Characteristics of legumes implemented in the FarmDyn model

		Alfalfa	Faba bean	Pea
Yield (t ha^{-1})	France	10.2	3.0	4.1
	Germany	8.5	4.2	4.7
Selling price (€ t^{-1})	France	-	208	212
	Germany	-	177	198
Buying price (€ t^{-1})	France	-	270	246
	Germany	-	297	306
N from mineralization of residues (kg N ha^{-1})	France	25	30	20
	Germany	20	10	10

One of the main advantages of legumes is their positive effect on subsequent crops. Their ability to fix N and the mineralization of their residues provide N available to subsequent crops. Thus, for a crop c, the per hectare N requirements $Nneed_c$ are covered by four sources[3]: N from previous year legume residues $Nleg_c$, N from manure $Nmanure_c$ and synthetic fertilizers $Nsynt_c$, and N from fixation of legumes $Nfix_c$ covering the N requirements of the respective legume and being zero for other crops:

$$Nneed_c \leq \ Nmanure_{\mathrm{c}} + Nsynt_c + Nleg_c + Nfix_c \qquad (1)$$

The N need considers unavoidable losses that occur during the application of synthetic N fertilizer. For manure, further N losses arising during storage and application are considered, respecting details of the application technique, the manure type, and the storage facility (Haenel et al. 2018). N requirements in FarmDyn are specified for each crop and not for the overall crop rotation, and fertilization activities are depicted with a monthly resolution to reflect environmental and economic impacts, such as seasonal leaching and emissions, labor requirements, and manure storage capacity. The amount of N mineralized from legume residues on one hectare $NcarryOver$ depends on the legume leg and varies with regional conditions, such as climate and soil. In this study, parameters relating to N from mineralization of residues are based on legal texts (COMIFER 2011; BMEL 2017).

Since FarmDyn is used as a comparative-static model without considering multiple plots, it is not known which crop follows after a specific legume. Therefore, a pool of N $NlegPool$ is calculated at farm scale by summing the given per hectare $NcarryOver_{leg}$ multiplied with the area X of each legume leg:

[3] In order to avoid quadratic terms in FarmDyn, the indicated variables relate to the total hectares of the crops in the model.

$$NLegPool = \sum_{leg} X_{leg} * NcarryOver_{leg} \tag{2}$$

This total N-pool $NLegPool$ is distributed to the different crop areas X (Eq. 3). To avoid implausible distributions to individual crops, on each hectare, their uptake of N mineralized legume residues $Nleg_c$ cannot exceed the maximum per hectare mineralization $NcarryOver$ of any legume (Eq. 4).

$$\sum_{c} X_c * Nleg_c = NlegPool \tag{3}$$

$$\text{with } \mathrm{Nleg_c} < \max_{\mathrm{leg}} \mathrm{NcarryOver} \tag{4}$$

The mineralization of legume residues adds another source of N that is integrated in the calculation of N leaching according to the model SALCA-NO_3 (Richner et al. 2014). The N response from different fertilizers can vary subject to their composition and the N compound. Among other factors, the N release time and N losses that occur during application or through leaching vary with the type of fertilizer. FarmDyn accounts for differences in the fertilizers in the calculation of N losses, for example by considering emissions from different N compounds, considering among other factors the month and technique of application, pasture grazing, and difference in manure storage facilities and storage times. However, differences in the N release time of different N compounds on the crop are not considered.

2.2.4 Differentiated implementation of the ND in the FarmDyn model

As all European directives, the ND (91/676/CEE, European Council 1991) must be implemented into national laws, which implies differences across member states. For our analysis, we introduce into FarmDyn the key aspects of the French and the German ND implemented in our case study regions (BMEL 2017; DREAL Pays de la Loire 2018) (Table 2.3). Apart from slightly different blocking periods for the application of manure, the main divergence relevant for this study is the possibility of spreading manure on legumes or not. In France, spreading manure on grain legumes (e.g. peas, faba beans) is forbidden, while it is allowed on forage legumes (e.g. alfalfa). In Germany, there is no threshold on the application of manure on legumes as long as the surplus of the nutrient balance at the farm gate does not exceed 50 kg N ha^{-1}. Both the French PDL region and the whole of Germany are designated as nitrate vulnerable zones where organic N application is limited to 170 kg N ha^{-1} on farm level.

Table 2.3 Main measures under the ND implemented in France and Germany

	France	Germany
Threshold of organic N application	170 kg N ha^{-1}	170 kg N ha^{-1}
Surplus of nutrient balance authorized at the farm gate	No regulation	50 kg N ha^{-1}
Threshold of organic N application on legumes	Alfalfa: 200 kg N ha^{-1} Grain legumes: 0 kg Na^{-1}	No regulation
Fixed blocking periods of N application	Crop planted in autumn: 15 November – 15 January Crop planted in spring: 01 July – 15 January Pasture and alfalfa: 15 December – 15 January Rapeseed: 01 November – 15 January	Grassland: 01 November – 31 January Arable land: 01 October – 31 November
Minimum manure storage capacity	4 to 6.5 months	LSU^{f}.ha^{-1} <3: 6 months LSU.ha^{-1} >3: 9 months

2.2.5 Sensitivity analysis

The effectiveness of implementing VCS for legumes and spreading manure on these crops is assessed based on a sensitivity analysis that considers different price levels. It covers the selling price of wheat and the buying prices of soybean meal and of three concentrated feeds as the main substitutes for legumes (Charrier et al. 2013). We distinguish three concentrates according to their raw protein content (12, 15, and 40 per cent). First, observed minimal and maximal prices (between 1995 and 2017) after adjusting for trends are derived from official statistics (Eurostat 2019), and related to the average price over the period. The resulting minimal and maximal fluctuations are applied to the initial average prices (DLR Westerwald Osteifel 2011; IDELE 2016; IFIP 2017; KTBL 2019), giving price ranges for each input (Table A2.1 in Appendix Chapter 2). Subsequently, adopting a similar approach to Kuhn et al. (2019) and Lengers et al. (2014), Latin hypercube sampling (LHS) is used to generate a representative price sample. For each tested policy scenario (see Section 2.6), 1,000 price samples are randomly drawn out of the calculated price ranges, assuming a uniform distribution. LHS divides the probability distribution ranges of each good into 1,000 intervals, ensuring an equal probability of each interval to depict closely the probability distribution. From each interval, one price sample is randomly selected and combined to price samples from the other goods (McKay et al. 2000). The specific LHS variant applied considers the correlation between the prices from the observed price series (Eurostat 2019) (Table A2.2 in Appendix Chapter 2).

For each price sample, FarmDyn simulates the optimal farm-level plan by maximizing the net present value. The sampled results are used in a descriptive statistical analysis to determine the performance of key indicators under the considered price ranges.

2.2.6 Scenarios

We define a baseline scenario (VCS0) with no VCS for legumes and the national implementation of the ND on each farm. In the first scenario (VCS100), we implement a VCS for legumes in both countries, keeping the national implementations of the ND. Even though the total VCS budget for legumes is stable among years in France, the VCS per hectare depends on the legume variety and on the total area of legume cultivated during the year. Therefore, we implemented the minimum level established in France: 100 € ha^{-1} for peas, faba beans, and alfalfa. In the second scenario (VCS100ge), the German ND is additionally introduced on the French farm. Lastly, we define a set of scenarios where the VCS per hectare is increased on both farms in increments of 10 per cent, starting from 110 to 300 € ha^{-1} (VCS110 to VCS300), under the French or the German ND on the French farm, and the German ND on the German farm. The highest level does not yet reach the coupled support under the MacSharry reform with, for instance, 73 € ha^{-1} for peas and faba beans (Bues et al. 2013). While it is unlikely to return to such levels of VCS, the resulting large shares of legumes, not yet observed on dairy farms, provide original information, particularly on their environmental impacts in intensive dairy systems.

2.3 Results and discussion

Unless specified, the following quoted values represent the median of our sample.

2.3.1 Legume shares and manure spreading

In the baseline scenario (VCS0), both farms produce three crops in addition to pasture: wheat, maize for silage, and one legume: peas on the French farm and faba beans on the German farm. These legumes are present on the farms only to comply with the EFA requirement and represent 5 per cent of the arable land on both farms (Table 2.4). The introduction of VCS of 100 € ha^{-1} on the French and German farms increases the share of legumes in the arable land. However, the results of the sensitivity analysis suggest that the legume share of the German farm remains lower compared to the French Farm (Figure 2.1). The share of 1,000 draws, in which the German farm grows legumes only to comply with the greening regulation, is particularly high. This difference can also be observed in the median. While the median legume share doubles to reach 10 per cent of arable land in France, it increases only to 7 per cent on the German farm (Table 2.4). Legumes substitute mainly against wheat, while the acreage of maize remains quasi-constant, since it is the main source of fodder for the dairy herd. Alfalfa is not yet produced with this level of VCS.

When the VCS per hectare gradually increases from 100 to 300 € ha^{-1}, the legume share continues to increase (Figure 2.2). On the French farm, first differences between the

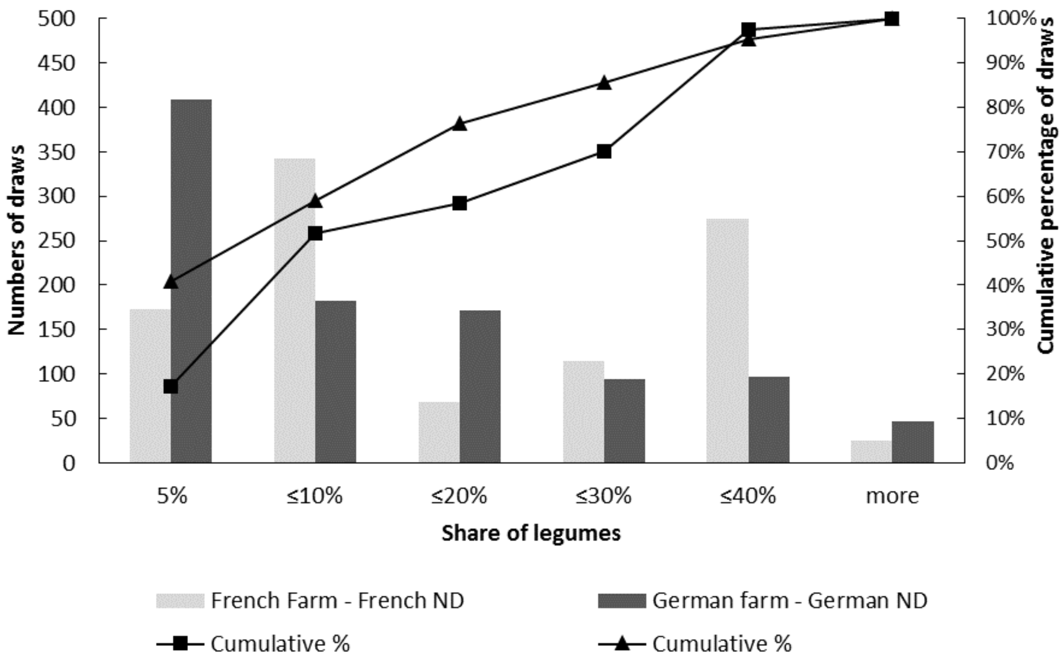

Figure 2.1 Distribution of share of legumes among the 1,000 draws implemented in the sensitivity analysis, for the French farm and the German farm with VCS of 100 € ha^{-1}

implementation of ND become apparent after VCS130. Under the French ND, the legume share grows consistently until it reaches its maximum of 34 per cent of arable land in VCS260: at this stage, the need to distribute all the manure prevents further increases of grain legumes on which manure application is prohibited. Alfalfa, on which manure application is allowed, has reached at this stage a production level where further substitution for protein-rich concentrates is no longer viable. Accordingly, under the German ND where manure can be distributed also to grain legumes, the overall legume share is higher and reaches 45 per cent of arable land in VCS300. Under the German ND, spreading of manure on grain legumes begins under VCS160 with 3 m^3 ha^{-1} of manure and reaches 14 m^3 ha^{-1} in VCS300 (Figure 2.2). From VCS220 to VCS250, the differences in legume shares between the ND are limited. At these levels of VCS, alfalfa becomes competitive and is introduced in increasing levels in the crop rotation. In contrast to grain legumes, the application of manure on alfalfa is also permitted under the French ND, which explains the limited differences in simulated crop shares. The increase in the legume share is always associated with a decline in the share of wheat, such that the acreage of maize remains constant. In VCS140, the median legume share under the French ND exceeds the median share under the German ND. Here, the difference is caused by different periods in which the spreading of manure is allowed.

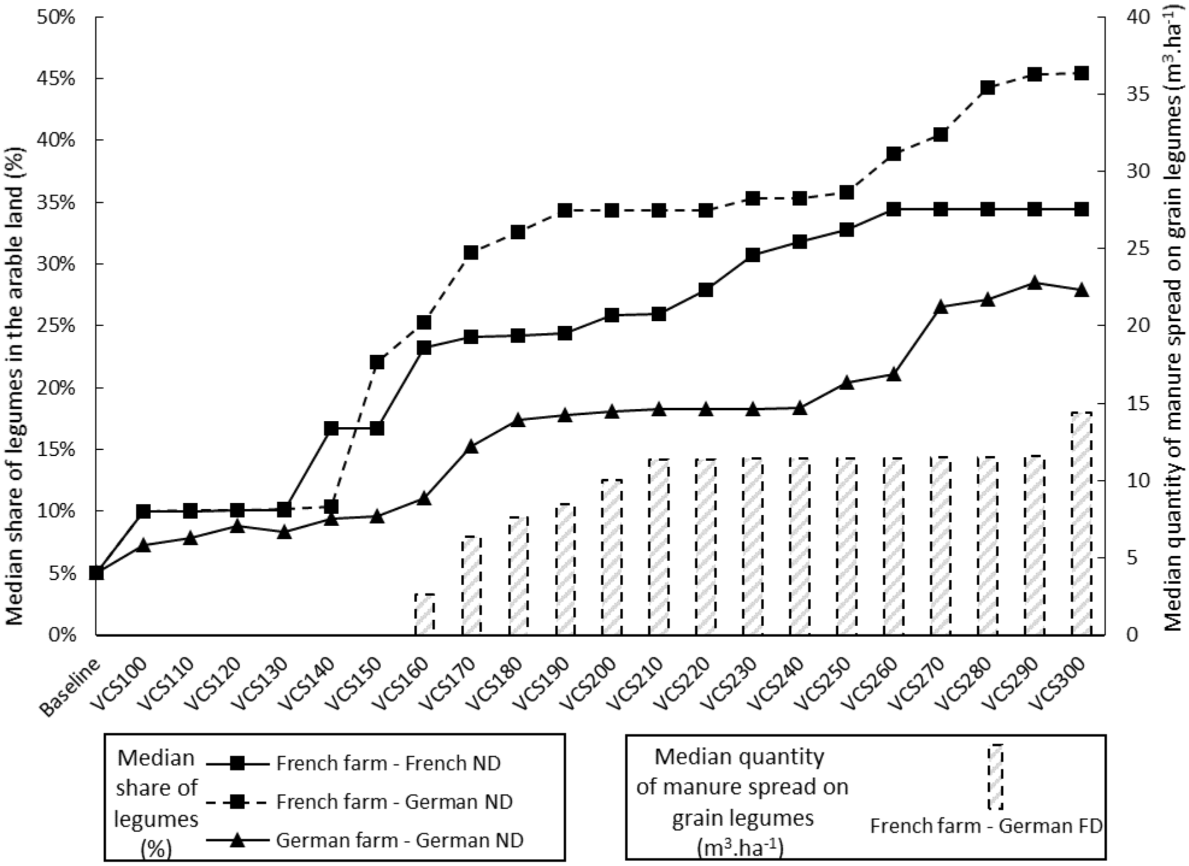

Figure 2.2 Share of legumes and quantity of manure spread on grain legumes (medians), per farm and implementation of the ND, under the VCS scenarios for legumes

On the German farm, the legume share slowly increases to reach a maximum of 28 per cent in VCS300 (Figure 2.2). As on the French farm, grain legumes (faba bean) substitute for wheat at quasi-constant maize production. The lower increase on the German farm is mainly due to the high prices and yields of wheat, which increase the opportunity costs of legumes. It is interesting to notice that the median quantity of manure spread on legumes on the German farm is equal to zero in all scenarios (Table 2.4).

Overall, the results suggest that VCS can effectively foster legume production in dairy farms, but that differences in crop productivity or livestock intensity matter, as seen from the lower response in Germany. These results are in line with findings of Helming et al. (2014) analyzing the effect of different policy measures that aim at increasing legume production in the EU. They found a maximum increase of 15 per cent in legume areas with subsidies from 210 to 422 € ha^{-1} and thus concluded that among other measures subsidies on legumes are an effective tool to increase legume share. However, their study is limited in scope since the results are not detailed by type of farm. It is necessary to stress out that, in our study, the sensitivity analysis shows large differences in legume shares on both farms at the same VCS level. Thus, the effectiveness of the VCS highly depends on the economic context. Besides, on the French farm under the German ND, the share of grain legumes reaches 38 per cent in scenario VCS300, which is above the often recommended maximum share of legumes in the crop rotation (25 per cent). However, such high shares do exist in organic systems in the EU (Pelzer et al. 2019).

2.3.2 Input use and protein self-sufficiency

The increase in legume production decreases the use of two major inputs. First, legumes produced on the farm substitute purchased feed and thus increase the farm's protein self-sufficiency (Figure 2.3). On the French farm, the protein self-sufficiency increases from 67 per cent in the baseline scenario to 71 per cent in scenario VCS220, under both NDs. Then, up to VCS300, the German ND fosters an additional increase to 74 per cent, while it consistently remains at 71 per cent under the French ND. This gap is mainly due to the additional production of alfalfa under the German ND. On the German farm, the increase in protein self-sufficiency is particularly high, with a baseline value lower than that on the French farm: it increases from 60 per cent in the baseline scenario to 71 per cent in VCS300. On both farms, most legumes are used as feed and are not sold to the market. This reveals a better profitability of legumes as intermediate goods (i.e. own-produced feed) than as final goods (i.e. cash crops). This is consistent with the results of Schläfke et al. (2014) who found a higher potential of legumes in dairying as on-farm feed than as cash crop. However, on the French farm (under both NDs) and on the German farm, the production of grain legumes exceeds the herd's needs; thus, grain legumes are sold as cash crops. Although it does not contribute to a further increase in protein self-sufficiency at farm level, it can nevertheless promote protein self-sufficiency at higher such as national scale.

The second input-saving effect is related to synthetic N fertilizer. Under VCS300, its use is reduced by 73 and 81 per cent on the French farm, respectively, under the French and the German ND, and by 66 per cent on the German farm compared to the baseline scenario. This reflects, first, that legumes provide N by mineralizing their residues. Second, the overall demand for N is lower as less wheat is produced, a crop with high N need and requiring higher use of mineral N, especially compared to maize. However, differences in N release times between the sources were not considered because FarmDyn does not incorporate sufficient details on relevant soil–plant–atmosphere interactions. To overcome this limitation, a linkage model between FarmDyn and a detailed crop model such as done recently by Kuhn et al. (2020) would be a valuable option.

Table 2.4 Results of main indicators (median and range) used in the integrated assessment, for selected scenarios, per farm and implementation of the Nitrates Directive (ND)

	French farm - French ND					French farm - German ND					German farm – German ND				
	VCS0	VCS100	VCS150	VCS200	VCS300	VCS0	VCS100	VCS150	VCS200	VCS300	VCS0	VCS100	VCS150	VCS200	VCS300
Share of legumes	5% (5-35)	10% (5-46)	17% (5-48)	26% (5-49)	34% (5-59)	5% (5-48)	10% (5-49)	22% (5-53)	34% (5-58)	45% (5-63)	5% (5-44)	7% (5-45)	10% (5-59)	18% (5-59)	28% (5-62)
Grain legumes	5%	7%	15%	24%	32%	5%	6%	20%	33%	38%	5%	5%	8%	18%	26%
Protein self-sufficiency	67% (58-86)	69% (58-89)	71% (58-91)	71% (58-92)	71% (58-92)	68% (58-90)	68% (54-92)	71% (58-92)	71% (56-92)	74% (59-92)	60% (54-88)	61% (49-89)	61% (54-90)	65% (49-91)	71% (54-92)
Manure on legumes (m^3 ha^{-1} legumes)	0 (0-10)	0 (0-15)	0 (0-15)	0 (0-15)	11 [a] (0-15)	0 (0-19)	0 (0-20)	0 (0-21)	10 (0-21)	14 (0-21)	0 (0-14)	0 (0-14)	0 (0-20)	0 (0-20)	0 (0-21)
Synthetic fertilizer (kg ha^{-1})	125 (35-131)	105 (23-131)	74 (22-131)	42 (21-131)	34 (11-131)	127 (22-134)	108 (21-136)	52 (17-134)	34 (13-136)	24 (8-134)	183 (34-185)	170 (29-188)	157 (18-185)	116 (17-189)	61 (11-184)
Farm Profit (k€ ha^{-1})	1.13 (1.05-1.25)	1.14 (1.07-1.27)	1.15 (1.09-1.25)	1.16 (1.10-1.26)	1.17 (1.13-1.26)	1.14 (1.05-1.27)	1.15 (1.08-1.29)	1.15 (1.09-1.27)	1.16 (1.11-1.27)	1.18 (1.14-1.27)	1.39 (1.25-1.64)	1.39 (1.27-1.61)	1.40 (1.29-1.63)	1.41 (1.31-1.62)	1.43 (1.34-1.63)
Share of VCS in profit	0.0% (0-0)	0.6% (0.3-2.4)	1.4% (0.4-3.7)	2.9% (0.6-5.0)	5.7% (0.9-9.1)	0.0% (0-0)	0.6% (0.3-2.5)	1.9% (0.4-4.0)	3.8% (0.6-5.8)	7.4% (0.8-9.6)	0.0% (0-0)	0.4% (0.3-2.1)	0.8% (0.4-4.1)	1.9% (0.6-5.5)	4.4% (0.8-8.5)
N leaching (kg N ha^{-1})	36 (22-41)	36 (19-41)	36 (19-41)	35 (19-41)	30 (18-41)	36 (20-39)	36 (19-42)	34 (19-48)	34 (19-48)	34 (17-52)	20 (7-23)	19 (7-23)	19 (6-31)	19 (6-32)	19 (6-36)
GWP (kg CO_2eq kg^{-1} milk)	1.25 (1.06-1.69)	1.21 (1.04-1.69)	1.21 (1.03-1.69)	1.20 (1.02-1.69)	1.16 (1.01-1.65)	1.23 (1.05-1.70)	1.23 (1.04-1.81)	1.22 (1.03-1.70)	1.22 (1.02-1.77)	1.21 (1.02-1.68)	1.37 (1.06-1.68)	1.30 (1.05-1.70)	1.29 (1.04-1.71)	1.29 (1.04-1.69)	1.26 (1.02-1.71)

Notes: The minimum and maximum values are in parentheses. [a] *Manure spread only on alfalfa.*

2.3.3 Environmental and economic indicators

The increase in the legume share leads to a slight improvement in environmental indicators on both farms (Figure 2.3), which partly reflects the associated decrease in input use. On the French farm, reductions in N leaching differ between the two NDs. Under the French ND, N leaching decreases almost continuously to reach a maximal decrease of 16 per cent in VCS300, whereas under the German ND it decreases only by 5 per cent. This gap is due to the spreading of manure on grain legumes, provoking their over fertilization and thus additional N leaching.

The GWP decreases by 5 per cent in VCS300 under the French ND and by 2 per cent with the German ND. The lower decrease under the German ND reflects two factors: higher input purchases and a higher production of alfalfa that causes emissions through the dehydration process. The profit of the French farm slightly increases by 4 per cent, with simultaneous rising revenue from VCS under both NDs. However, the total VCS allocated under the German ND is higher than that under the French ND (as the legume share is higher). Since the simultaneous decrease in GWP is lower, the GWP abatement costs diverge widely between the NDs: under the French ND, they reach 26 € t^{-1} CO2eq in VCS100 and 130 € t^{-1} CO_2eq in VCS300, while under the German ND, they reach 190 € t^{-1} CO_2eq in VCS100 and 1,040 € t^{-1} CO_2eq in VCS300.

On the German farm, the improvement in environmental indicators is similar. N leaching decreases by 5 per cent under VCS300 and GWP by 7 per cent, while the farm profit slightly increases by 3 per cent. Even if the decrease in GWP on the German farm is similar to the decrease on the French farm under the French ND, abatement costs are far lower, reaching a maximum of 81 € t^{-1} CO2eq in VCS300 but only 12 € t^{-1} CO_2eq in VCS100. At this stage, the abatement costs on the German farm are lower than the prices of European Emission Allowances (observed spot prices in 2019 range between 18 and 30 € t^{-1} CO_2eq) (European Commission 2020).

On both dairy farms, methane from enteric fermentation is the main source of GWP. This explains why increasing the legume share has only a limited impact on this indicator. Similarly, Gaudino et al. (2018) find that reduction in GHGs can be mainly achieved by herd reductions. The slight decreases in N are coherent with the findings of Nemecek et al. (2008), who focused on environmental impacts of legumes in cropping systems only.

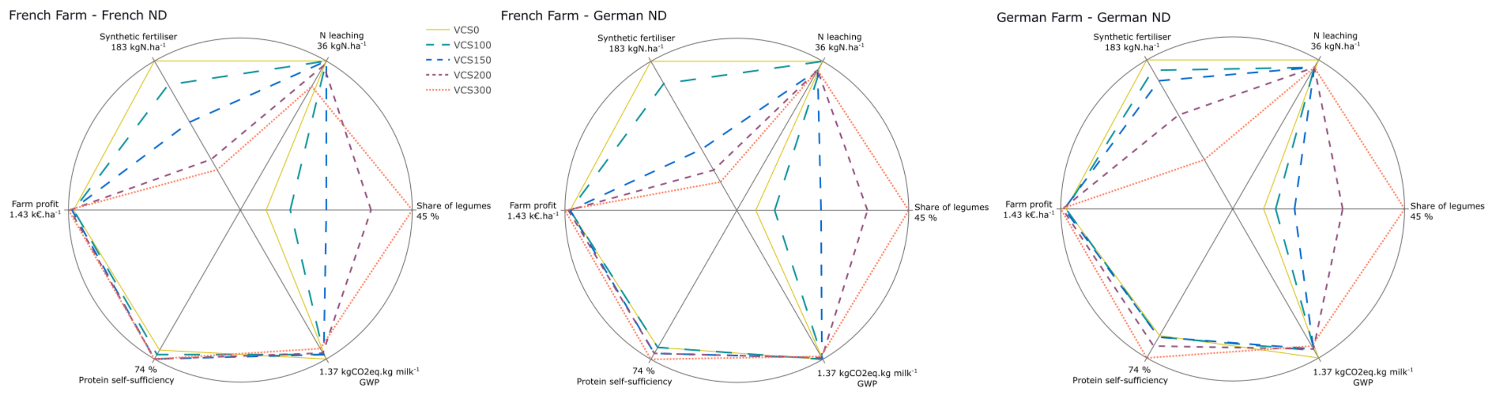

Figure 2.3 Integrated assessment of farms, across specific scenarios and ND implementation

Notes: The chart compares economic and environmental indicators across different levels of VCS for each farm and implementation of the ND. For each indicator, the upper boundary is defined by the maximum value observed in the study, across all case studies and scenarios. The minimum value is set zero for all indicators.

2.3.4 *Policy implications and future research*

This study is the first one that assesses the interactions of two key policy measures affecting legume production in Europe: VCS for legumes and the national implementation of the ND. In particular, it addresses the issue of interacting policy measures that, on the one hand, aim to promote legume production and, on the other hand, potentially constrain their production by regulating N supply. To do so, we employ the bio-economic model FarmDyn, integrating economic and environmental dimensions of two dairy farms. Based on a sensitivity analysis, the effectiveness of the policy measures is assessed regarding different price levels of five inputs or outputs. We found that relatively low VCS of 100 € ha^{-1} represents an effective tool to provoke a first increase in legume production. Although further research is needed to get a wider picture of the impact of such coupled support, this finding is in line with the recent study of Cortignani and Dono (2020) who investigate levers to develop rotation with legumes as part of the next CAP. However, medium to high VCS must be implemented to reach the shares of legumes targeted in the study of Cortignani and Dono (2020), which raises questions in terms of economic efficiency of VCS. Thus, we recommend a combination with other measures that lower the opportunity costs of legumes in order to foster their production. In particular, implementing a tax on N synthetic fertilizer to internalize their negative externalities might be an interesting option to promote legume production on farms (Henseler et al. 2020).

Our study shows that large legume shares induced by high VCS do not lead to substantial environmental benefits in the analyzed dairy farms. This provides a complementary picture to most other studies that focus on legumes on arable farms. Our findings suggest that the impacts of crop diversification on environmental sustainability of livestock farms are limited. However, the inclusion of other indicators, in particular indicators oriented toward biodiversity, might revise this conclusion. The limited impacts reflect that a large part of the externalities analyzed in this study are related to the herd itself: N leaching and emissions from manure handling and enteric fermentation represent the main source of climate-relevant emissions. This suggests more ambitious agro-environmental measures that directly target animal production, such as stricter regulations in terms of livestock density or manure handling. Similarly, other current policies, such as Greening, also seem to reach limited results in terms of improved environmental status (Gocht et al. 2017). In these views, the Green Deal may represent a unique opportunity to improve the sustainability of this essential economic sector (Peyraud and MacLeod 2020).

Depending on the level of support and input prices, allowing manure spreading on grain legumes on the French farm, as possible under the German ND, can increase the legume share by up to 7 percentage points. However, it does not lead to substantial improvements of environmental indicators. Thus, this policy change can be justified only by other goals such as improving protein self-sufficiency. Allowing manure application to grain legumes could be more relevant on farms facing higher livestock densities where the manure spreading area is a factor restricting even limited legume shares. Nevertheless, restrictions should be set regarding the maximum amounts of manure allowed on these crops in order to avoid a rise of N leaching. Indeed, a substantial decrease in N leaching requires a new regulatory paradigm: fertilization practices should be adapted to meet the real needs of crops through in-depth monitoring, now possible thanks to the development of big data and new types of sensors (Martins et al. 2020).

Even if the improvement in environmental indicators is limited, we still observed considerable decreases in N-rich input uses. High levels of VCS combined with the possibility of spreading manure on grain legumes lead to a considerable decrease in the use of synthetic N fertilizers and soybean meal. Notably, reduced imports of soybean and its meal are on the European political agenda in the context of so-called imported deforestation (European Parliament 2011; Pendrill et al. 2019). However, existing World Trade Organization regulation makes it impossible to directly limit imports of soybean. Initiatives from private stakeholders might instead encourage farmers to grow legumes. For example, the development of certified GMO-free milk, produced from animals fed with legumes produced locally, represents an interesting lever to increase the profitability of legumes as feed, while improving the protein self-sufficiency of farms (Jouan et al. 2020b). However, this innovation must be supported by policies to ease processing of legumes at farm level, such as investments in specific storage and improved sorting (Meynard et al. 2018).

Our study concerns two representative case studies in prominent dairy production areas and gives first insights into the interactions of two key policy measures affecting legume production in Europe. Clearly, a larger sample of farms of different types and from different regions is needed to generalize our findings. However, the strength of our analysis lies in the nature of the sensitivity analysis carried out. It considers the market environment of main substitutes of legumes at farm level: wheat as output, and soybean meal and concentrates as inputs. In addition, it would also be possible to carry out a sensitivity analysis on the yields of legumes, which vary more than those of other crops (Cernay et al. 2015). Such an analysis could also consider that a decline of pollinators might reduce legume yields (Biesmeijer et al. 2006; Garratt et al. 2014). Further research could also include pollinator supporting activities in the assessment, such as floral strips (Häussler et al. 2017). Indeed, such landscape infrastructures are already promoted by the ‘Greening’ as EFA but they could benefit from stricter regulation to increase their implementation (Pe'er et al. 2017).

In this study, we focused on the interaction between VCS and the ND. Further policy fields could be considered, such as interactions between VCS and pesticide policies.

Conventional legume production still mostly relies on pesticides, while certain regulations ban pesticides on these crops, such as the UE 2017/1155 that prohibits pesticides on legumes used as EFA. This restriction—which might lead to lower yields and/or higher costs for mechanical plant protection measures—is not considered in our analysis, but is mainly irrelevant as the 5 per cent legume level linked to fulfilling the EFA requirement is already found in the benchmark. In addition, our case studies suggest that it is more profitable to use legumes as own-produced feed than to sell them on markets. More studies analyzing the profitability of legumes used as feed, and not only as cash crops should be developed. Beyond the farm level, it would be interesting to study crop–livestock integration through exchanges of legumes (i.e. crop farms selling legumes to livestock farms) or through the export of manure (i.e. livestock farm exporting manure to crop farms) (Moraine et al. 2016; Willems et al. 2016; Jouan et al. 2020a). However, when working at regional or even higher scale, policy feedback should be included as the total VCS budgets for each legume species are upper bounded at national level. Indeed, this bound is necessary to remain in compliance with the World Trade Organization 'blue box' criteria (Regulation No. 1307/2013).

Finally, we deliberately analyzed high levels of VCS to explore implications of high legume shares not yet observed in conventional farms. Such legume shares make farm profit more dependent on subsidies, which is a doubtful strategy at a time where high subsidies under the CAP are questioned. Indeed, a considerable increase in the production of legumes on livestock farms requires implementing a set of measures that combine regulatory constraints, coupled support, and investment aid to sectors promoting these crops such as the emerging sector of GMO-free feed.

2.4 Conclusion

Despite their contribution to a more sustainable agriculture, legume production remains low in the EU. This study assesses economic and environmental impacts of two key policy measures affecting legume production in the EU: VCS for legumes and the national implementations of the ND. It compares in detail a French and a German representative dairy farm, taking into account legumes as own-produced feed and as cash crops. When VCS is implemented, the legume production increases, but to a more limited extent on the German than on the French farm, due to higher opportunity costs of legumes in Germany. On both farms, the increase in legume production leads to limited decrease in N leaching and GWP. On the French farm, the implementation of the German ND associated with high VCS leads to a further increase in the legume share. Thus, allowing manure spreading on grain legumes, as allowed by the German ND, can help to increase production of legumes in dairy farms with high livestock densities. However, it hardly reduces N leaching in our case studies as manure applications exceed the N needs of legumes. Due to the dominance of methane emissions from enteric fermentation in dairy farms, we observe a limited impact on GHG emissions. Allowing manure spreading on grain legumes to increase their crop share can still be justified by other goals, such as decreasing the imports of soybean for feed. Overall, to considerably increase the production of legumes on livestock farms, it is essential to implement a set of measures that combine regulatory constraints, production subsidies, and investment aid to other sectors promoting these crops such as the emerging sector of GMO-free feed.

2.5 Acknowledgements

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Chapter 3

Economic effects of plot sizes and farm-plot distances in organic and conventional farming systems: A farm-level analysis for Germany[4]

Abstract

Plot sizes and farm-plot distances affect the economic performance of agricultural production. Their economic effects likely differ between conventional and organic farming systems due to major differences in crop production programs. Our paper quantifies these effects based on big data on resource requirements of field operations, summarized by regression models. Combined with detailed case study information obtained through interviews, we assess plot size and farm-plot distance effects for three case study farms which recently converted to organic farming. Our results show for both farming systems, as expected, that larger plot sizes reduce labor requirements and costs associated with crop production while larger farm-plot distances increase them. At same plot sizes and farm-plot distances organic farms face lower costs in crop production and, at given market prices, higher profits. Cost savings from larger plot sizes are, however, higher in conventional farming systems as are cost increases from growing farm-plot distances. This implies that economic benefits of conversion are higher for farms managing smaller plots farther away from the farm. Land fragmentation might hence favor switching to organic production and motivate regionally differentiated subsidy rates.

Keywords

economic performance, organic farming, conventional farming, plot size, farm-plot distance, big data analysis

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3.1 Introduction

Organic agriculture is considered promising to address growing societal concerns related to environmental pollution from farming, animal welfare, and food quality and safety. A larger set of policy instruments, implemented at the European and national levels, supports the development of organic farming. As part of the National Sustainable Development Strategy, the German government aims to increase the share of organic farming on productive agricultural land from 9% in 2018 (BMEL 2018) to 20% by 2030 (German Federal Government 2018). Currently, the 12% of organic farms are somewhat smaller in farm size compared to their conventional counterparts (BMEL 2018). A large body of literature analyzes factors driving decisions to switch from conventional to organic farming, considering for example characteristics of the farmer and intrinsic motivations (Koesling et al. 2008; Padel 2001; Storstad and Bjørkhaug 2003; Xu et al. 2018), or biogeographic factors (Pautasso et al. 2016). However, there is evidence that economic considerations gain importance and conversion to organic farming increasingly develops to an economic decision (Koesling et al. 2008).

Economic implications of conversion have been widely studied, including for example policy support, impacts of risks as well as price premiums (Kallas et al. 2010; Nieberg and Offermann 2003; Pietola and Lansik 2001; Uematsu and Mishra 2012). None of the studies, however, addresses how varying plot sizes and farm-plot distances, i.e. the distance of the plot from the farm building, affect input requirements of field operations and thus the relative economic performance of organic and conventional systems.

Economic effects of plot sizes in agricultural production have been mainly addressed in the context of land fragmentation. Increasing plot sizes provide economies of scale by reducing unproductive turning and driving times of field operations. The resulting input savings, for instance of labor and fuel, decrease average costs of production (Herrmann and Papesch 1996; Jahns et al. 1983; Latruffe and Piet 2014; Looga et al. 2018; Lu et al. 2018). Increasing farm-plot distances have the opposite effect by increasing resource requirements and costs of field operations due to higher transport costs (Jahns et al. 1983; Kuhlmann 2015; Latruffe and Piet 2014). The impacts of plot sizes and farm-plot distances highly depend on the type and the number of field operations (Jahns et al. 1983). Distance matters most for field operations with high transport volumes, such as for harvest processes, where travel times accounts for a large share of work. Input requirements of tillage and other field operations with low working widths are, however, more sensitive to changes in plot sizes.

The type and the number of field operations as well as the amount of intermediate and final products transported depend highly on the crop rotation and the crop management (Kuhlmann 2015) and thus differ between conventional and organic farming systems. These differences are, for example, caused by restrictions on the use of synthetic fertilizer under organic production, causing a shift towards the application of manure and the cultivation of legumes. Further, a ban on chemical synthetic pesticides increases the importance of mechanical weed control measures in organic production systems. As a result of the differences, economic effects of plot sizes and farm-plot distances likely differ between these farming systems and might influence the decision of conversion.

Conversion processes are highly divergent, as changes in farm program depend, for instance, on location factors such as soil and climate and access to market. Besides changes in crop production, conversion is often associated with an introduction of livestock or changes in livestock management and related fodder production. Therefore, comparisons between organic and conventional farming should consider the whole farm with its different branches such as arable and livestock production (Nemes 2009).

This study addresses a gap in the literature by analyzing the effects of plot sizes and farm-plot distances on the economic performance in organic and conventional farming systems. The effects are estimated by applying a regression model to big data on field operations to determine the impact of plot sizes and farm-field distances on resource requirements. However, when switching from conventional to organic the whole farm management must be considered rather than changes of individual field operations for a single crop. We therefore assess costs of crop production, profits and labor requirements at the level of the whole farm for three case studies. We capture different farm specializations by analyzing an arable crop farm, a pig fattening operation, and a dairy farm in the region of Western Germany. Detailed information before and after conversion are collected to assess the changes in the farm program and related changes in field operations. By linking the case study data to the results of the regression analysis on big data on field operation, we simulate effects of increasing plot sizes and farm-plot distances under the conventional and organic production programs. Further, we discuss potential impacts on the decision of conversion.

3.2 Method

The effects of plot sizes and farm-plot distances in conventional and organic farming systems are evaluated by linking big data on field operations to detailed case study data for a large-scale sensitivity analysis (see Figure 3.1). The big data reports necessary field operations and related resource requirements for 145 crops under the conventional and organic farming system, considering distinct plot sizes and farm-plot distances. Based on a regression analysis, we derive from there continuous functional relations of how costs and labor requirements of field operations depend on plot sizes and farm-plot distances. Detailed case study farm data are collected with interviews, providing information on the conventional and organic production programs (crop shares, share of crop production sold or fed, herd sizes, labor and housing requirements, etc.) as well as key economic indicators such as selling prices and input cost. The information on each case study are complemented by detailed planning data on costs and revenues of livestock and crop production. By linking the regression functions to the case study data, the profit, costs and labor requirements of each farm are calculated as function of plot sizes and farm-plot distances. The functions are used to conduct a large-scale sensitivity analysis on the effects of plot sizes and farm-plot distances in the conventional and organic production system. The economic performance of the case study farms is assessed by applying the functions to observed plot sizes and farm-plot distances.

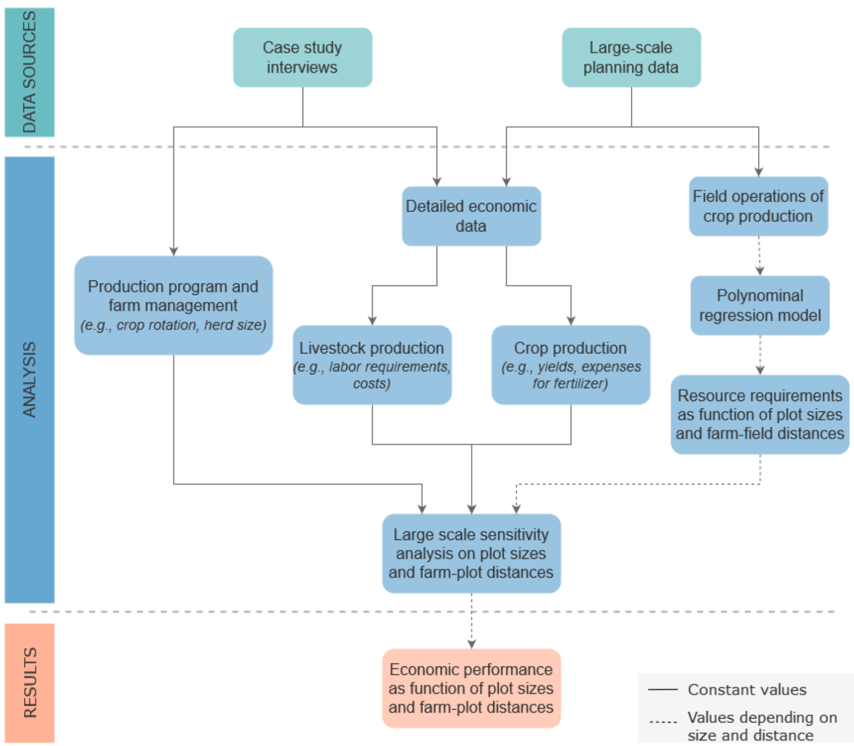

Figure 3.1 Overview of methodological approach

3.2.1 Large scale planning data

The large-scale database from the *Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL)* provides detailed planning data, including economic data and data for environmental accounting, for various farm branches such as arable, livestock and horticultural production. Experts from various disciplines constantly update the database by bundling data from market observations, field experiments and research projects as well as expert assessments and manufacturer surveys. Data cover both conventional and organic production systems. The database primary serves as a basis for planning calculations and business assessments on German farms, but it also regularly used for policy assessments, research and education. The database is partly extracted using web scraping methods.[5]

The economic data on livestock production provide details on revenues and costs as well as labor requirements, separated by the type of livestock and farming system (i.e. conventional or organic production). The data reflect characteristics of livestock management, such as the type of housing, feeding choices and herd sizes, as well as the level of performance (e.g. milk yield and length of the lactation period, slaughter weight, livestock losses). The data are expressed per year and stable place (KTBL 2019c).

The information for each crop include data on yields and prices as well as expenses for agricultural contractors and direct costs (e.g. planting materials, fertilizers and pesticides) (KTBL 2019a). Further costs are related to machine applications for required field operations (e.g. tillage, sowing, application of pesticides). The data report required field operations with details on costs of machine applications, including, for instance, machinery depreciation and costs for maintenance, lubricants and fuel. Labor requirements are quantified, considering for example time spent on turning, transportation and preparation. All data are differentiated by mechanization levels, which reflect substitution possibilities between labor and capital and costs in crop production. Labor savings and changes in capital and other costs from using larger machinery depend on plot sizes, farm-plot distances and performed field operations. They differ between conventional and organic farming systems, reflecting system specific field operations. All data are provided in detail for 145 crops, including for example main crops and catch crops, under conventional and organic production.

3.2.2 Regression model

Labor requirements and costs of machine applications are highly dependent on plot sizes and farm-plot distances. The database provides details for distinct plot sizes, farm-plot distances and mechanization levels, separated by farming system (conventional vs. organic), amounting to more than 29.5 million data records (KTBL 2019b). As an example, Appendix 3.A illustrates the required field operations and related costs of conventional and organic winter wheat production. The data are used to derive a regression model by crop, field operation and farming system to express labor and resource requirements as a function of plot sizes and farm-plot distances. We consider plot sizes of up to 40 ha, farm-plot distances up to 30 km and three mechanization levels (with tractors of 67 kW, 102 kW and 200 kW as main machine). It is assumed that farms operating with the lowest mechanization level rely

[5] The applied web scraping methods is available online (see: https://github.com/fruchtfolge/ktbl-apis)

on contractors for field operations that require high mechanization (e.g. ensilaging). In that case, no labor requirements arise. Contrary, with 102 and 200 kW, all field operations are managed autonomously.

We estimate for each field operation FO, crop C, mechanization level M and farming system S the different per hectare resource requirements based on a polynomial regression function with plot size P and farm-plot distance D as explanatory variables:

$$\hat{Y}_{FO_{C_{SM}}} = \beta_0 + \beta_1 P + \beta_2 P^2 + \beta_3 \sqrt{P} + \beta_4 D + \beta_5 D^2 + \beta_6 PD \quad (1)$$

$$\hat{Y}_{C_{SM}} = \sum_{FO} \hat{Y}_{FO_{C_{SM}}} \quad (2)$$

In total, we provide 1.8 million regression functions covering 8 positions (such as fuel and labor requirements, maintenance and interest costs) of field operations for 145 crops. The specific polynomial form shown above was selected from alternatives using the distribution of the Akaike information criterion. The model provides a high goodness-of-fit with only 10% of the 1.8 million regression functions having an adjusted R-squared lower than 92%, the median being 97%. The root mean squared deviation (RSMD) normalized by the mean observed values is generally convincing, with 90% being lower than 7% and a median of 2%. More details on the model selection and its performance can be found in Appendix Chapter 3.

For each crop, the regression coefficients for labor and resource requirements are summed over the required field operations. This yields per hectare labor as well as intermediate resource requirements related to machine applications for a crop, as a function of plot sizes and farm-plot distances, differentiated by three mechanization levels.

3.2.3 Case study data

In Germany, the share of organic farming in productive agricultural land increased from 3% in 2000 and 6% in 2010 to 9% in 2018 (BMEL 2019a, 2019b). In 2018, 32,000 organic farms managed more than 1.5 million hectares, of which 56% are permanent grassland and 42% arable land. Most of the arable land under organic production is dedicated to the cultivation of cereal grains, plants harvested green (including fodder legumes) and grain legumes (e.g. lupines, beans and peas) (DESTATIS 2017). 70% of the organic farms are engaged in livestock production, 75% of which produce cattle and 10% pigs. Organic farming accounts for 6% and 1% of the German cattle and pig production respectively (BMEL 2019b). In the western German states of North Rhine-Westphalia and Lower Saxony, the share of organic farming in agricultural land is the lowest in Germany, at 6% and 4.7%

respectively. Here, the national aim of achieving 20% by 2030 remains particularly ambitious (BMEL 2020; German Federal Government 2018).

We analyze as case studies three farms located in Western Germany. An arable farm, a pig fattening farm and a dairy farm are selected to cover the relevant farm types in this region. The farms are selected as representative by consultants of the Chamber of Agriculture after personal communication (LWK NDS 2019; LWK NRW 2019a; 2019b). We collect with semi-structured face-to-face interviews relevant technical and economic information on crop and livestock production, covering for example the production program as well as prices and yields where available. Key results are reported in Table 3.1. All three farms have been recently converted from conventional to organic production such that we receive detailed information about the farm program under both systems. The first farm is specialized in arable production and added laying hens in mobile housing as a farm branch under the organic system. This allows the integration of a grass-clover mix as pasture in the crop rotation to capture nitrogen. The second farm, specialized in pig fattening and managed part-time, downsized its operation with regard to both acreage and number of livestock when switching to the organic system. This reflects increasing labor requirements per unit of livestock and higher stable place requirements in the organic system, reducing maximal herd sizes in the existent housings. A change in livestock husbandry, where the farmer buys piglets at an earlier age, enables a more efficient exploitation of existing housings. Field beans as legumes are introduced to the crop rotation. The third farm slightly expanded its dairy herd when switching to organic and marginally reduced the average milk yield per cow. With solely one cow per hectare and a 47% grassland share, the farm was managed rather extensively already under the conventional system. It used its remaining land mainly for cereal production as well as grain and silage maize. After conversion, 90% of the land is devoted to grass and grass-clover production; the remaining 10% provide whole crop silage from cereals.

Table 3.1 Key attributes of the case study farms

		Arable Farm		Pig Fattening Farm		Dairy Farm	
		Conventional	Organic	Conventional	Organic	Conventional	Organic
Farm size	ha	100	100	56	42	100	100
Number of livestock places			2,500	800	240	100	105
Crop shares	%	Sugar beet (35%) Wheat (25%) Barley (25%) Potatoes (15%)	Grass-clover (17%) Grain peas (17%) Triticale (17%) Potatoes (13%) Barley (12%) Wheat (8%) Spelt (8%) Pumpkin (4%) Grain maize (4%) Catch crop (30%)	Wheat (46%) Barley (27%) Silage maize (27%) Catch crop (27%)	Grain maize (25%) Field bean (20%) Triticale (20%) Barley (20%) Wheat (10%) Oat (5%) Catch Crop (15%)	Grass-clover (32%) Permanent Grassland (15%) Grain maize (15%) Silage maize (12%) Rye (11%) Barley (7%) Wheat (5%) Oat (2%) Catch crop (10%)	Grass-clover (75%) Permanent grassland (15%) Whole crop silage (10%) Catch crop (10%)
Average farm-plot distance	km	0.5		1.1		2	
Average plot size	ha	5.1		6		4	

Notes: Key attributes of the case study farms as reported in face-to-face interviews.

3.2.4 Effect size and economic performance

The effects of plot sizes and farm-plot distances are estimated by determining economic performance indicators of the case study farms as a function of plot sizes and farm-field distances. The assessment is based on the profit, costs related to crop production and labor requirements, arising both in crop production and at farm level. Costs related to the production of a crop are calculated by adding resource requirements of field operations estimated with the regression model (section 3.2.2) to direct costs per hectare such as seeds, fertilizer and plant protection products and arising expenses for agricultural contractors (section 3.2.1) (see Appendix A3.C). These results are weighted with the observed crop shares to derive for each case study farm average costs per hectare under the conventional and organic production system.

To the degree possible, profits are calculated using yields and prices provided in interviews. Otherwise, prices from KTBL are used (KTBL 2019a). For fodder crops only used inside the farm, no price or yield information is needed. Subsidies granted to organic production are included, considering differences in premium levels for organic arable and grassland production (BLE 2015). Costs and revenues arising in livestock production stem from KTBL (2019c), considering the farms stocking density to arrive at per hectare values.

To isolate the effects of plot sizes and farm-plot distances, the farms' sizes in terms of total hectare remain constant within the study, which implies a decreasing number of plots with increasing plot size. Labor requirements are determined by adding the labor demand of livestock production per hectare and the estimated labor demand of field operations. Labor costs are considered in the cost and profit calculation, assuming wage costs of 20 € per hour (IG Bauen-Agrar-Umwelt et al. 2019). All economic results are reported on per hectare basis.

The economic data on livestock production as well as revenues and direct costs of crop production are independent of plot sizes and farm-plot distances. By linking the results of the regression model to data not varying by plot size or farm-plot distance, overall farms profit, costs and labor requirements are determined as a function of plot size and farm-plot distance, differentiated by three mechanization levels. From there, only the cost minimizing mechanization level for each point on the function is maintained, assuming one general mechanization level for all operations.

Using this function, we generate a three-dimensional surface area for each of the economic indicators. For each plot size and farm-plot distance, the cost minimizing mechanization level is chosen such that the surface can be composed of different polynomial regression functions. A linear regression on the three-dimensional surfaces is performed with plot size and farm-plot distance as explanatory variables to determine the average effects of plot sizes and farm-plot distances. The function is subsequently used to calculate the economic performance of the case study farms at observed plot size and farm-plot distance and to assess average effects of plot sizes and farm-plot distances.

3.3 Results

3.3.1 Economic performance

For all three farms, conversion to organic farming is in the observed period a profit increasing choice. Figure 3.2 shows the calculated economic performance of the three case study farms at observed plot sizes and farm-plot distances. A key reason for the higher profits under organic production is the large price premium for organic outputs. The milk price received, for instance, increases by almost two thirds (from 0.28 to 0.46 € kg^{-1}) while *the* price obtained for fattened pigs more than doubles (from 1.56 to 3.99 € kg^{-1}). Before conversion, the average profits per hectare differ considerably between the three case study farms, with the arable farm generating a positive profit of 610 € ha^{-1}, while the pig fattening and the dairy farm face negative profits of −246 € ha^{-1} and -280 € ha^{-1}. We find that the profit of the pig fattening farm is higher under the organic system even without considering subsidies, increasing with conversion to 1056 € ha^{-1} for organic production. In contrast, the profit of the arable farm before subsidies decreases after conversion to 466 € ha^{-1}. The change in profits before subsidies for the dairy farm is limited and remains almost constant at −295 € ha^{-1}. Once subsidies granted for organic production are considered, all three farms achieve higher profits compared to conventional production. The realized profits increase to 726 € ha^{-1} in the arable farm and to 1316 € ha^{-1} in the pig fattening farm. In the dairy farm, however, profits remain negative with −71 € ha^{-1} under the assumed wage costs of 20 € h^{-1}.

We find that costs per hectare related to crop production are 8% lower in the organic system on average over the three case studies. The reduction reflects three drivers. First, the crop rotation shifts towards crops requiring fewer inputs. For example, all three farms either introduced or expanded legume production which requires no nitrogen fertilization. Second, direct costs are reduced as mechanical weed control does not require additional inputs as opposed to chemical one and costs for synthetic fertilizer are omitted. The direct costs, mainly related to fertilizers, pesticides and planting materials, decrease from 465 to 263 € ha^{-1} on average over the case study farms. Third, less frequent fertilization and plant protection measures in organic farming cause a lower number of machine passes over the fields for most crops. This decreases expenses related to machine applications, such as diesel and machinery maintenance, from 675 to 580 € ha^{-1}, as well as related labor requirements and costs. However, the crop production costs of the arable farm slightly increase, reflecting a strong increase in labor requirements.

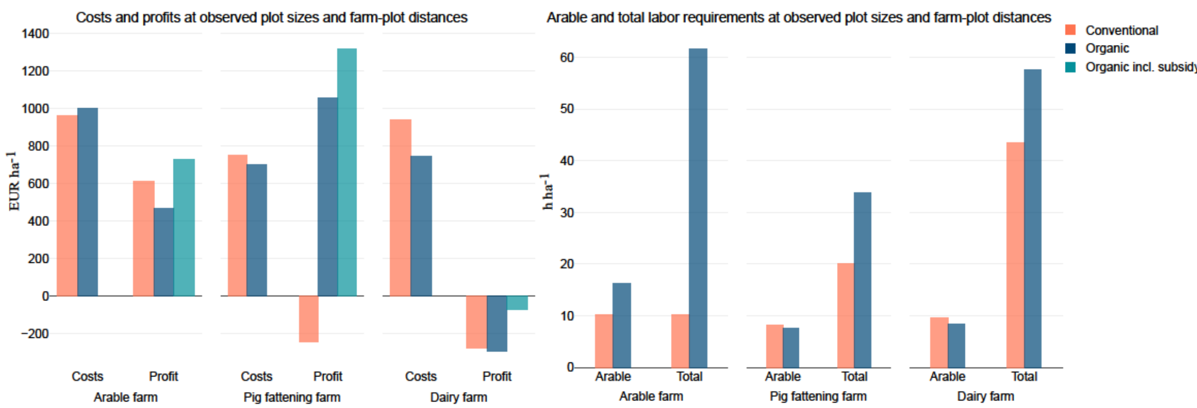

Figure 3.2 Overview on the calculated economic performance at observed plot size and farm-plot distance

Notes: The economic performance is presented for the conventional and organic production program at plot sizes and farm-plot distances reported by the farmers. Costs include the costs of on-farm labor, valued at 20 € h^{-1}.

Our results show lower labor requirements related to crop production after conversion in the pig fattening and dairy farm, decreasing from 8.2 to 7.5 h ha^{-1} and from 9.5 to 8.4 h ha^{-1}, respectively. For the arable farm, labor requirements in crop production increase, however, from 10.3 to 16.2 h ha^{-1}. This reflects rather labor intensive weed control, harvesting and post-harvest processes for pumpkin as a new crop in the rotation. The introduction of laying hens in the former specialized arable system without livestock adds considerably further labor requirements, such that in total 61.7 h ha^{-1} are required. Similarly, when including animal production, the total labor requirements of the pig fattening and the dairy farm increase after conversion, from 20.1 to 33.8 h ha^{-1} and from 43.4 to 57.6 h ha^{-1}, respectively. In those two farms, when switching from conventional to organic production, labor savings in crop production are offset by increased labor requirements in livestock production.

3.3.2 Effects of plot sizes and farm-plot distances

Next, we look at the results of the large-scale sensitivity analysis on the effects of plot sizes and farm-plot distances. Figure 3.3 shows the profit of the three case study farms as function of farm-plot distances and plot sizes, including subsidies granted for organic production.[6] The arable farm generates positive profits under both production systems regardless of plot sizes and farm-plot distances. In contrast, the pig farm only generates positive profits under organic production while the profit of the dairy farm is negative before as well as after conversion.

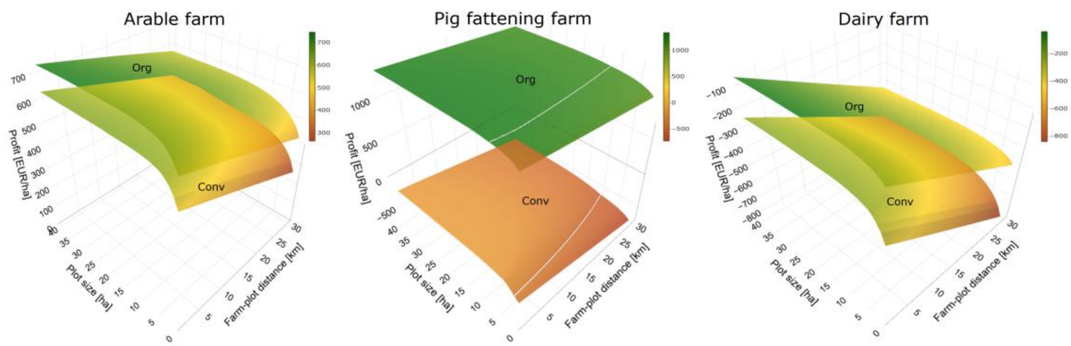

Figure 3.3 Profit [€ ha^{-1}] as a function of plot size and farm-plot distance

Notes: Profit in conventional (conv) and organic (org) farming system including organic subsidy and costs of 20 € h^{-1} for on-farm labor. Shown is the cost minimizing mechanization level.

[6] The graphs are part of interactive graphs, available online. Further interactive graphs, depicting the costs and labor requirements of the three case studies as function of plot size and farm-plot distances are provided alike. https://chrispahm.github.io/Economic-Effects-Distance-Plot-Size/

Table 3.2 Average effects of plot size and farm-plot distance on profits [€ ha^{-1}], costs [€ ha^{-1}] and labor requirements [h ha^{-1}]

	Arable farm		Pig fattening farm		Dairy farm	
	Conv	Org	Conv	Org	Conv	Org
	EST *(SE)*	EST *(SE)*	EST *(SE)*	EST *(SE)*	EST *(SE)*	EST *(SE)*
Intercept						
Profit incl. org. subsidy [€ ha^{-1}]		722 *(0.18)*		1,313 *(0.21)*		-48 *(0.10)*
Profit without org. subsidy [€ ha^{-1}]	604 *(0.18)*	462 *(0.18)*	-253 *(0.34)*	1,053 *(0.21)*	-261 *(0.26)*	-272 *(0.10)*
Costs of crop production [€ ha^{-1}]	967 *(0.18)*	1,005 *(0.18)*	759 *(0.34)*	704 *(0.21)*	922 *(0.26)*	719 *(0.10)*
Coefficients						
Farm-plot distance [(1)] [€ ha^{-1}]	-7.24 *(0.01)*	-6.22 *(0.01)*	-11.75 *(0.01)*	-6.17 *(0.01)*	-13.98 *(0.01)*	-13.26 *(0.00)*
Plot size [(1)] [€ ha^{-1}]	1.91 *(0.01)*	1.44 *(0.01)*	3.42 *(0.01)*	1.68 *(0.01)*	2.19 *(0.01)*	0.66 *(0.00)*
Intercept						
Total labor requirements [h ha^{-1}]	10 *(0.00)*	62[(2)] *(0.00)*	20 *(0.01)*	34[(3)] *(0.01)*	43 *(0.00)*	57[(3)] *(0.01)*
Arable labor requirements [h ha^{-1}]	10 *(0.00)*	16 *(0.00)*	8 *(0.01)*	8 *(0.01)*	9 *(0.00)*	8 *(0.01)*
Coefficients						
Farm-plot distance [h ha^{-1}]	0.17 *(0.00)*	0.14 *(0.00)*	0.25 *(0.00)*	0.11 *(0.00)*	0.24 *(0.00)*	0.22 *(0.00)*
Plot size [h ha^{-1}]	-0.05 *(0.00)*	-0.03 *(0.00)*	-0.09 *(0.00)*	-0.07 *(0.00)*	-0.04 *(0.00)*	-0.01 *(0.00)*

Notes: Coefficients of the linear regressions on the three-dimensional surfaces for conventional (conv) and organic (org) production. Stated are the estimates (EST) and the respective standard errors (SE). [(1)] The coefficient is the same for profits and costs, however, the direction of the effect is inverse [(2)] impact of integrating livestock in production system, [(3)] reflects higher labor demands of specific requirements in organic livestock production.

Figure 3.2 presents the results of the linear regression on the three-dimensional surfaces for the three case study farms separated by farming system. The regression coefficients, i.e. the effects of plot sizes and farm-plot distances, measure the change in profits, costs and labor requirements for changes of one hectare in plot size and one kilometer in farm-plot distance, respectively. Given the relatively small effects, the intercepts show again that profits of organic production including subsidies granted to organic production are higher for all three case study farms. Without considering these subsidies, the arable farm generates higher profits under conventional production while the pig fattening farms still achieves a higher profitability under organic production. The profit maximizing farming system without these subsidies for the dairy farm is not distinct but depends on the plot size and the farm-plot distance.

As indicated by the regression coefficients in Figure 3.2, the average effects of plot sizes and farm-plot distances are in absolute terms stronger for conventional production in all three case study farms. This is especially relevant for the pig fattening farm: an increase in farm-plot distance by one kilometer provokes an increase in costs by 11.75 € ha^{-1} under conventional compared to 6.17 € ha^{-1} under organic production. Similarly, an increase in plot size by one hectare reduces costs by −3.42 € ha^{-1} under conventional compared to −1.68 € ha^{-1} under organic production. On average over the three case study farms, the effects of plot sizes and farm-plot distances on costs and profits are 80% higher under conventional production. One reason is the higher number of machinery passes for most crops in conventional farming. This implies that overall costs increase stronger with increasing farm-plot distances and decreasing plot sizes compared to organic production. For the dairy farm, the effects of farm-plot distances are the highest. This relates mostly to the high transport quantities related to fodder production on grasslands.

The effects on the labor requirements follow these trends. Labor savings in crop production from larger plot sizes and smaller transport distances are on average 74% higher in conventional farming. On the pig fattening farm, for example, labor requirements related to crop production increase by 0.25 h ha^{-1} under conventional and by 0.11 h ha^{-1} under organic production with an additional kilometer of distance. Increasing plot sizes reduce labor requirements here by −0.09 h ha^{-1} and by −0.07 h ha^{-1} farm. The total labor requirements of the analyzed farms, except for the conventional production program of the arable farm, mostly relate to livestock production. This strongly reduces the relevance of the analyzed effects at farm level. As livestock production per hectare is assumed constant, total changes in labor requirements per hectare are equal to changes in labor requirements in crop production. Similarly, absolute decreases of costs per hectare in crop production are equal to absolute increases in overall farm profits per hectare.

3.4 Discussion

3.4.1 Economic performance of conventional and organic farming systems

For any plot sizes and farm-plot distances considered in the study, organic farming remains the profit maximizing choice for the case study farms. This is in line with previous studies finding higher profits in organic farming (e.g. Hanson et al. 1997; Kerselaers et al. 2007; Nieberg and Offermann 2003). These observations contrast with the still quite low share of 9% (BMEL 2018) of agricultural land under organic production in Germany. In this context, it should be considered that, first, organic farmers face higher production risks related to quantity and quality (Gardebroek et al. 2010). Second, higher profits for organic systems to a large extent reflect price premiums which depend on access to organic value chains. The latter might, however, not always be given. It has for example been reported in the media that organic dairies in Germany do not award additional delivery contracts, preventing conversion (Landwirt 2020; Welt 2018).

In addition to high price premiums, the higher profits of organic production partly arise from lower costs in crop production, mostly from reduced direct costs and from a lower number of passes over the field with consequences on labor and machinery requirements. Similarly, Mahoney et al. (2007) and Nemes (2009) stress the relevance of lower production costs on the higher profitability of organic production.

The labor requirements of organic crop production are lower for most crops. However, the often necessary switch to a more diversified crop rotation can also introduce labor intensive crops as observed on our arable case study farm. The high labor requirements in livestock production of organic farming additionally provoke higher total labor requirements for all three case studies. This fits the findings of previous studies, revealing that organic farms face higher labor requirements per hectare and are managed more labor intensive (Delbridge et al. 2013; Jansen 2000; Offermann and Nieberg 2000; Reissig et al. 2016).

3.4.2 Effects of plot sizes and farm-plot distances

The results of the study show the expected direction of the effects of plot sizes and farm-plot distances: larger plot sizes increase economic performance by reducing labor requirements and costs associated with crop production. In contrast, growing farm-plot distances drive up costs and labor requirements. Similar economic effects of plot sizes and farm-plot distances have been found for different regions (Latruffe and Piet 2014; Looga et al. 2018; Lu et al. 2018). These studies used micro data from farms with different land fragmentation in cost functions and regression analyses, and therefore consider implicitly potential adjustment of crop shares to plot size and farm-plot distances. In this context Kuhlmann (2015) reports that increasing farm-plot distances provoke changes towards less intensive crop rotations. Our study is thus complementary, as the effects are calculated at fixed crop shares and based on detailed data collected, for instance, by field experiments. Omitting changes in the crop rotation thus allows to explicitly isolate the effects on the economic farm performance irrespective of changes in management measures. Latruffe and Piet (2014) find plot sizes and farm-plot distance not only affecting costs but also yields and thus, revenues of crop production. Lacking other information, crop yields in here are independent of plot sizes and farm-plot distances and as observed on the study farms under both systems, i.e. before and after conversion. If crop yields react to plot sizes and farm-plot distances, the effects of plot sizes and farm-plot distances might be even of higher importance for profits as revenues are affected as well.

3.4.3 Impact on conversion decision

Higher effects of plot sizes and farm-plot distances are found in conventional farming systems. This implies that costs savings from large plot sizes and small distances are stronger for conventional farms while adverse effects of small plots and large farm-plot distances are lower for organic farming systems. Nonetheless, independent of the plot size and the farm-plot distance, the profits are higher under organic production for our case studies of farms which converted recently to organic farming. This selection bias renders its likely to find a positive effect on profits, compared to analyzing a sample of farms staying in the conventional system. Nevertheless, the economic benefits of conversion increase with decreasing plot sizes and increasing farm-plot distances. It can hence be concluded that incentives to switch to organic production are stronger in landscape settings where plot sizes are limited and joining plots to larger fields is hard. Further, organic farms have advantages when putting bids on smaller plots farther away from the farms.

Currently, organic farming is unevenly distributed within Germany. Studies by Schmidtner et al. (2012) and Petersen et al. (2020) found that in Germany conversion to organic farming is higher in regions with poor soil quality and high shares of protected nature areas and permanent grassland. Similar, results of Früh-Müller et al. (2019) indicate that expenditures on agri-environmental payments, including payments granted for organic farming and conversion, vary significantly across Germany. Regions characterized by intensive agriculture, exhibiting high livestock densities, large farm sizes and high yield potential, receive significantly less payments. Maps of geographical information systems indicate that in Germany the share of organic production in the agricultural area is higher in federal states with smaller average plot sizes. In 2018, five of seven federal states (excluding city states) with more than 10% organic agricultural production exhibit Germany's smallest plots (BMEL 2018; OneSoil n.d). Further, with on average 48 ha, organic farms are smaller than conventional farm which encompass on average 65 ha (BMEL 2018). Hence, organic farming systems are more frequent in regions characterized by lower production intensities and greater land fragmentation. We shed light on the last factor: potential profit gains from switching to organic production are smaller on large plots and short farm-plot distances. It can thus be concluded that regional conversion rates are influenced by present spatial structures and plot sizes and farm-plot distances contribute to the spatial concentration of organic farms.

A large body of literature studies the conversion to organic farming and its determinants. Many variables were found to impact the conversion, including farmers characteristics and attitudes (e.g. Koesling et al. 2008; Padel 2001) and economic considerations (e.g. Nieberg and Offermann 2003; Pietola and Lansik 2001). From our study it can be concluded that plot sizes and farm-plot distances impact economic considerations of the farmers conversion decision and accordingly add new factors to the wide discussion on conversion (Kallas et al. 2010). Our results thus can contribute to a better understanding of the adaption of organic farming and a more targeted promotion of organic farming systems.

3.4.4 Implications on policy and research

The aim of Germany's National Sustainable Development Strategy is to increase the share of organic farming to 20% of the productive agricultural land by 2030. A body of literature discusses the question of whether the expansion of organic farming should be spatial evenly distributed or whether a concentration on certain locations or regions is favorable, c.f. (Taube et al. 2006). In intensive production areas, converting to organic farming can significantly improve environmental conditions (Früh-Müller et al. 2018). However, this requires higher subsidies to reflect differences in opportunity costs of conversion. The effects of plot sizes and farm-plot distances additionally reduce the economic benefits of organic agriculture in intensively managed, low fragmented regions, reinforcing the need for higher incentives.

The study is conducted based on case study analysis, giving first insights into the differentiated effects of plot sizes and farm-plot distances on the economic performance of conventional and organic farms. The strength of the analysis lies in the nature of the large-scale sensitivity analysis using big data. In contrast to empirical analysis, this enables an estimation of regression equations in which resource requirements of field operations are represented as a function of plot sizes and farm-plot distances. The regression equations can also be applied in mathematical modeling approaches. The extension of farm scale models with the regression equations allows assessing the impact of plot sizes and farm-plot distances on management decisions and farm performance indicators, and, for example, how they interact with various policy instruments.

Clearly, a larger sample of farms from different regions is needed to generalize our findings. This is hampered by two important data limitations. First, as underlined by our case studies, switching from conventional to organic farming affects a farm in many aspects. An isolated analysis of the effects of plot sizes and farm-plot distances, as done in this study, requires observations before and after conversion, with detail in farm management. Such observations are quite scarce in existing single farm records such as the Farm Accountancy Data Network (FADN). Second, an integrated analysis of the effects using large samples requires data on actual plot size and farm-plot distances of farms. These are currently not part of official statistics (e.g. FADN and Farm Structure Survey). It might therefore be beneficial to study the relation between the spatial distribution of organic and conventional farming systems and land fragmentation using data provided by geographical information systems.

3.5 Conclusion

This study is the first to assess the effects of plot sizes and farm-plot distances on the economic performance of conventional and organic farming systems. We apply a regression model to big data on resource requirements of field operations for more than hundred crops. Thereby, we derive various cost positions and labor requirements per hectare as a function of plot size and farm-plot distance. These functions are of interest beyond the study, for instance, as a database in farm scale modeling, and provide a promising tool to provide further insights into the effects of plot sizes and farm-plot distances. By linking those to detailed information of three case study farms which recently converted to organic farming, we conduct a large-scale sensitivity analysis on effects of plot-sizes and farm-plot distances. We find for all case studies higher profits after conversion. Our results suggest that the effects of increasing plot sizes and farm-plot distances are considerably higher in conventional systems. Therefore, organic farms save less costs and labor per hectare when plot sizes increase or farm-plot distances decrease. Economic benefits of conversion are thus higher for farms operating in more fragmented land markets which might motivate regionally differentiated subsidy rates. A far larger sample of farms from different regions would be needed to generalize our findings. However, data on land fragmentation are missing in official agricultural statistics. Studying the relationship between the spatial distribution of organic and conventional farming systems and land fragmentation using data provided by geographical information systems might be a promising alternative.

3.6 Acknowledgements

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Chapter 4

The economic potential of organic production for stockless arable farms importing biogas digestate: A case study analysis for western Germany [7]

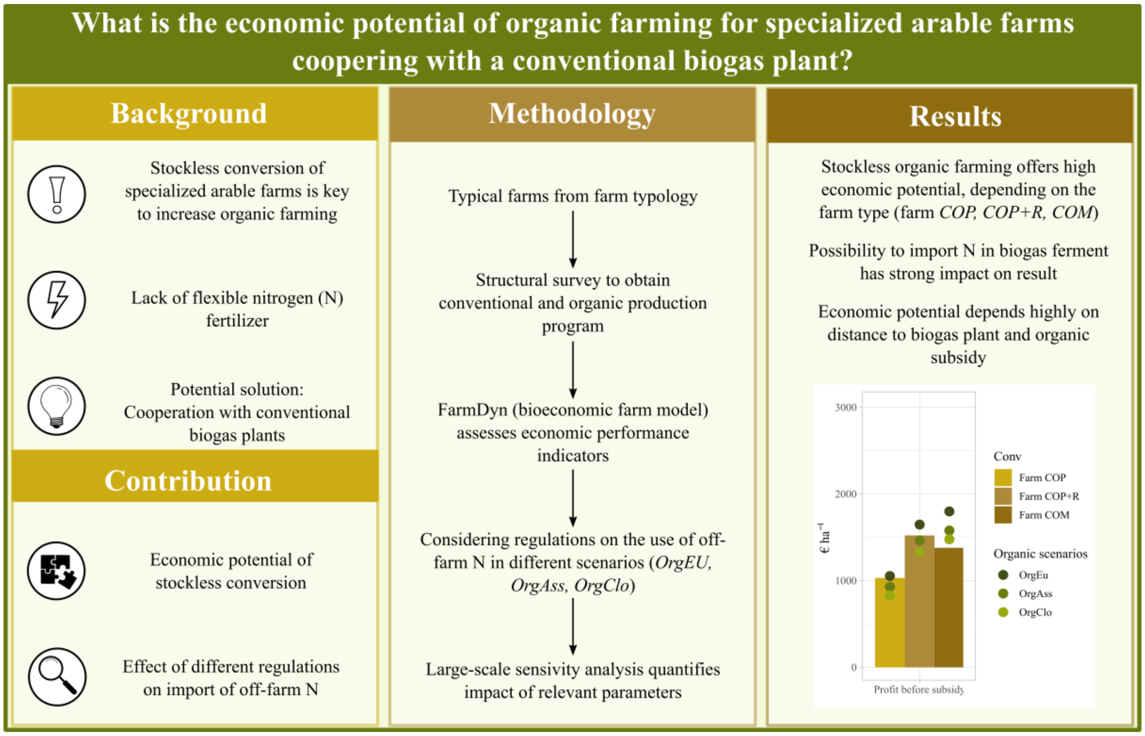

Figure 4.1 Graphical Abstract

Abstract

Context: Most stockless organic farms depend on the import of organic nitrogen. Biogas digestates offer an interesting solution to address this need for flexible nitrogen fertilizers. Their application could support the conversion of specialized arable farms,

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This study is part of the LIFT ('Low-Input Farming and Territories – Integrating knowledge for improving ecosystem-based farming') project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 770747. Part of this research was done within the Bioeconomy Science Center (BioSC) FocusLab "Transform2Bio". The scientific activities of the BioSC were financially supported by the Ministry of Culture and Science within the framework of the NRW Strategieprojekt BioSc (No. 313/323–400–002 13).

contributing to the politically targeted expansion of organic production. However, various regulations on the use of off-farm biogas digestates exist, which differ considerably in allowed N imports. Despite the growing interest in the application of biogas digestates in stockless organic farming in practice and research, its impacts on the economic potential of converting from conventional to organic farming have not been investigated.

***Objective*:** This study assesses the economic potential of organic production for specialized arable farms without taking up animal production based on cooperating with a conventional biogas plant. The study considers the impacts of different regulations on importing off-farm biogas digestates.

***Methods*:** The assessment employs the bio-economic farm model FarmDyn to evaluate multiple economic performance indicators for three stockless arable case study farms with varying cropping patterns under conventional and organic production. The German federal state of North Rhine-Westphalia serves as the case study area. A large-scale sensitivity analysis quantifies the impact of relevant parameters with a high uncertainty or possible large impact.

***Results and conclusions*:** Our results suggest that organic farming has a high economic potential for specialized arable farms when biogas digestate is applied. Taking existing subsidies into account, organic farming economically outperforms conventional production for all assessed farms and regulatory scenarios. However, stronger restrictions on the application of biogas digestates shift crop rotations toward higher shares of crops with low nutrient requirements and legumes. This reduces, especially in case of fodder legumes, revenues and increases labor requirements, and lowers profitability and labor productivity. Distance to the biogas plant and subsidies for organic production impact strongly on profitability, whereas input prices show small effects. Results underline that the economic performance of stockless organic farming depends highly on import possibilities of nutrients. Furthermore, they suggest that subsidies for organic farming should better reflect its economic potential across farm types to reduce deadweight effects and boost conversion where it is costly.

Significance: The study is the first to assess the impact of different regulations governing the import of fermentation substrates on the economic potential of stockless organic farming for specialized arable farms. This is relevant as conversion of stockless arable farms is lagging behind but could considerably contribute to reach policy targets for organic production.

Keywords

stockless organic production, conversion to organic farming, economic potential, biogas digestate, biogas, bio-economic farm model

4.1 Introduction

Organic production is considered promising to address growing societal concerns related to animal welfare and environmental externalities from agriculture. The European Commission intends to reach at least 25% of organic farming on the EU agricultural land by 2030 (e.g. EC 2020). The German Government is even more ambitious, aiming to increase this share from 11% in 2021 (BLE 2022) to 30% by 2030 (SPD et al. 2021). Despite an increasing number of German farms converting, this trend is not sufficient to achieve this goal (BLE 2022). Traditionally, organic farming systems include both crop and livestock production (Stinner et al. 2008), reflecting the principle of a closed on-farm nutrient cycle. However, the uptake of livestock production by specialized arable farms is associated with considerable investment requirements and an increased workload (Preston 2008; Schmidt 2003). In addition, other economic and organizational reasons, such as limited space and challenging approval processes for stables, along with farmers' preferences, hamper the uptake of livestock production during conversion (Schmidt 2003).

Increased conversion without introducing livestock seems key to reach EU and German policy targets related to organic farming. Of 16.7 million ha of agricultural land in Germany, 70% was arable land in 2016 (BMEL 2019), with the share of organically managed arable land being particularly low at 4.1%. Specialized arable farms account for >30% of all farms and, with 6 million ha, manage more than half of Germany's arable land, surpassing any other farm type (BMEL 2019).

Stockless organic farms, however, face specific challenges. They lack on-farm mobile nitrogen (N) fertilizer, which, along with the ban on mineral N fertilizers in organic farming, results in high N deficits and a tendency for low nutrient efficiency (Beckmann et al. 2000; Foissy et al. 2013; Stinner et al. 2006). As cooperations with organic livestock farms to exchange N-rich fodder for manure are not always possible, alternative strategies are warranted for N imports (Borgen et al. 2012). An increasingly popular approach is the use of digestates stemming from the fermentation of clover-grass delivered to a biogas plant (Maaß et al. 2017). Similar to livestock manure, biogas digestates provide a mobile, N-rich fertilizer that allows for spatially and temporally targeted distribution of nutrients (Möller et al. 2006; Stinner et al. 2008). In Germany, biogas production is highly present with 9,632 plants in 2020 (Fachverband Biogas 2021), creating promising conditions for an increased use of biogas digestates in organic farming. The EU regulation on organic farming generally permits the (unlimited) use of conventional off-farm biogas digestates in organic production[8] (EC 2021). However, additional regulations apply on the application of nutrients, which are also relevant for conventional farms. Nevertheless, a closed nutrient cycle is considered a fundamental principle of organic farming, resulting in the ban of mineral fertilizer and limits on nutrient imports from organic sources. The closed nutrient cycle, however, is only a guiding idea as selling of products and nutrient losses to the environment are inherent to farming systems. To better reflect these principles, organic farming associations impose stricter rules on the allowed N import from biogas digestates than the EU regulations. Limits depend, for example, on the N comprised in the biomass delivered to the biogas plant, and they consider additional restrictions on the use of digestates from conventional substrates.

Stockless organic farming is gaining importance in Germany, with its share in organic farms increasing from 25% in 2010 to 34% in 2020 (Destatis 2021). Nevertheless, the body of literature focusing on stockless production is still limited and questions about its economic performance remain (Taramarcaz and Clerc 2013). Results of previous studies suggest that the economic performance of stockless arable farms can increase with conversion, provided that the farm can import off-farm nutrients from livestock (Ács et al. 2007; Taube et al. 2005). Without manure application, the economic performance of organic farms, however, decreases (Taramarcaz and Clerc 2013). As a result, the lack of organic fertilizer is considered an important barrier for conversion (Łuczka and Kalinowski 2020). Generally, the anaerobic digestion of biomass and the return of biogas digestates can increase the economic performance of stockless organic farming systems, mainly due to the yield-increasing effects of flexible N fertilizers (Blumenstein et al. 2017; Blumenstein et al. 2020; Brock et al. 2017). Cooperation with an external biogas plant thereby offers highest economic performance (Serdjuk et al. 2018), since large investments, knowledge and building space are not required. Existing research focused on comparing organic systems with and without the use of biogas digestate. However, an assessment of the economic potential for specialized conventional arable farms to convert to organic farming with the use of biogas digestate is still missing.

To fill this gap, this paper examines the economic potential of stockless organic production for specialized conventional arable farms in a case study for Germany. The focus is here on stockless farms which cooperate with an external biogas plant to exchange biomass for biogas digestate. The study takes different regulations on the use of biogas digestate in organic farming into account, considering the EU regulation as well as stricter

[8] Manure originating from industrial livestock production is prohibited. This is defined based on a livestock density limit of 2.5 livestock units per ha.

rules of organic farming associations. This research applies a bio-economic farm model based on mixed-integer linear programming. Such models represent valuable tools for an ex-ante assessment of conversion to organic farming, as they capture in detail the economic and bio-physical dimensions of farming activities. This includes the depiction of crop nutrient needs and relevant nutrient flows, such as between a biogas plant and a farm. As farm models optimize management decisions from the viewpoint of the farmer, they are especially suitable to assess farm-level adoption of technologies and farming practices.

The federal state of North Rhine-Westphalia (NRW) serves as a case study area. Here, intensive production areas with high soil quality and low shares of permanent grassland are located, where conversion to organic farming is lagging, reflecting high costs of conversion (Schmidtner et al. 2012). With only 4% of all farms and 2% of arable farms being managed organically, the discrepancy to the targeted share is particularly pronounced (IT NRW 2018). Despite specialized arable farming being the dominant farm type (IT NRW 2021), the share of stockless operations in organic farms is below the national average at only 21% (IT NRW 2021). At the same time, the density of biogas plants on agricultural land is one of the highest in Germany (AEE 2020), suggesting a high potential for cooperation between biogas plants and organic farms.

4.2 Methods

4.2.1 Case study region and farms

Divided into nine different soil-climate regions (SCR), NRW is among the most divers agricultural regions in Germany (Roßberg et al. 2007). Arable production is predominantly located in three fertile SCRs: SCR 141, SCR 142 and SCR 143[9]. For each of these three SCR, one statistically representative arable farm is studied, based on the farm typology by Kuhn and Schäfer (2018), which follows the EU farm typology (EC 2008). According to the share of managed land the most relevant arable farm types are '*specialist cereals, oilseeds, protein crops'* (COP) in SCR 143, '*cereals, oilseeds, protein crops and root crops combined'* (COP+R) in SCR 141 and '*various field crops combined'* (COM) in SCR 142. For each farm type and SCR, the farm typology provides information on average farm sizes and crop shares (Table 4.1). Jointly, they manage 23% of the agricultural area and account for 24% of all farms in NRW (Kuhn and Schäfer 2018).

[9] 141: Cologne-Aachen lowland, 142: middle Upper Rhine, Lower Rhine, 143: Eastern Westphalia-Lippe (Roßberg et al. 2007)

Given that just 2% of arable farms are managed organically, these shares are assumed to represent the conventional production system and provide the basis to develop a conventional and organic crop rotation for each case study farm. The crop rotations are the result of a structured survey of a panel of agricultural consultants. Information on the survey is provided in the Appendix Chapter 4 (Appendix A4.A).

5-year averages on yields in conventional and organic farming systems are collected for NRW (Land-Data 2021), complemented by values for Germany when missing (KTBL 2019b). Yield levels are adjusted for each SCR to account for regional differences (JKI 2019; Pahmeyer 2021). Prices for conventional and organic products reflect averages for the period 2011 2020 (AMI 2021), complemented where required by KTBL (2019b). Price and yield data are reviewed by an expert panel and adjusted where deemed necessary. They can be found in Appendix Chapter 4, along with further regional data (Appendix A4.B).

Table 4.1 Key attributes of the case study farms

Case study	SCR	Farm type	Farm size [ha]	Observed crop shares [%]		Derived crop rotations[a]	
						Conventional	Organic
Farm COP	143	151[b]	29	WW WB WR WTri GM	36.0 20.2 19.1 5.5 4.3	1st WR 2nd WW 3rd GM* & WTri 4th WW 5th WB	1st CL 2nd WR 3rd SW* 4th FB 5th SP 6th SB*
Farm COP+R	141	162[c]	64	WW SB WR GM PO	42.6 23.0 6.7 3.5 2.3	1st WW 2nd WR & GM* 3rd WB 4th SuB* & PO*	1st CL 2nd GM & PO 3rd WW 4th FB 5th SP 6th WB & Oat*
Farm COM	142	166[d]	34	WW GM PO WB SB	27.7 19.4 10.4 9.3 8.9	1st SuB* & PO* 2nd WW 3rd GM* 4th WB & WW	1st CL 2nd GM 3rd WW 4th SOY* 5th PO* 6th SB* & Oat*

*Notes: The farm size represents the median size of all farms of the respective farm type in this region. Observed crop shares do not add up to 100%, remaining shares are allocated to crops with lower shares (Kuhn and Schäfer 2018); a Result of a structured survey (Appendix 4.A); b Specialist cereals, oilseeds, protein crops (151); b Cereals, oilseeds, protein crops and root crops combined (162); d Various field crops combined (166), * Catch crop before main crop; SCR – Soil-climate region; WW – Winter wheat; WB – Winter barley; WTr – Winter triticale; SP – Spelt; SB – Summer barley; SW – Summer wheat; GM – Grain maize; PO – Potato; SuB – Sugar beet; WR – Winter rapeseed; FB – Field beans; SOY – Soybeans; CL – Clover-grass.*

4.2.2 Scenario description

Under conventional production, the application of fertilizers, including biogas digestates, is regulated by the German Fertilization Ordinance (Bundesgesetzblatt 2020). In organic farming systems, further restrictions by regulations of the EU and private organic farming associations apply (Table 4.2). The EU regulation mainly imposes restrictions on the materials underlying the substrates used in biogas plants, while limits on the amount of N applied are identical to conventional farms based on the Nitrates Directive (EC 2018, 2021). Organic farming associations further restrict the maximum application rates of N and limit the amount of conventional off-farm N, while stricter regulations apply to materials used in biogas plants (Table 4.2). In Germany, 50.3% of organic farms are managed under the stricter rules of an organic farming association (Moewius et al. 2019). The largest farming associations, by number of members, are Bioland, Naturland, Demeter and Biokreis, together covering >90% of all farms in organic farming associations (Moewius et al. 2019). As Demeter prohibits stockless production, it is excluded from the analysis.

Table 4.2 Regulation on the use of biogas digestates in organic farming systems

	EU regulation	Biokreis	Bioland	Naturland
Max. N application	170 kg N ha^{-1} from livestock manure	112 kg N ha^{-1}	112 kg N ha^{-1}	112 kg N ha^{-1}
Max. quantity of conv. off-farm N [a]	No limit	+50% of N in exported biomass *and* 40 kg N ha^{-1}	40 kg N ha^{-1}	+15% of N in exported biomass [b] *and* 40 kg N ha^{-1}
Allowed fermentation substrates from conventional production				
Farmyard manure				
Ruminants and horses	YES	YES	YES	YES
Pigs	YES	NO	NO	YES
Poultry	YES	NO	NO	NO
Liquid manure, slurry	YES	NO	NO	NO
Renewable biomass [c]	YES	YES	YES	YES

Notes: Manure from factory farming (>2.5 GV ha^{-1}, pigs mainly on slatted floor, poultry kept in cages) is prohibited. [a] Nutrient exchange not considered as import; [b] Relates to ammonium-N in substrate, about 50% of the total N; [c] Without genetically modified material. (Biokreis 2022; Bioland e.V. 2022; European Commission (EC) 2018, 2021; Naturland 2022).

The study distinguishes between two types of N supply: First, *Nexchange*, i.e., the amount of N in farm-produced biomass that is delivered to an external biogas plant and taken back as biogas digestate. *Nexchange* is determined based on N equivalent exchange and not considered as off-farm N. Second, *Nimport*, which covers N in biogas digestate that is imported into the farm in addition to *Nexchange*. In a first scenario, *OrgEU*, the EU regulation on organic production is applied (Table 4.3). The amount of off-farm N, *Nimport*, that can be imported to the farm is only restricted by the German Fertilization Ordinance. The second scenario, *OrgAss*, covers the stricter rules of organic farming associations. Here, the maximum amount of *Nimport* depends on *Nexchange*, hence the amount of N delivered to the biogas plant and taken back after fermentation The allowed amount of *Nimport* is set at 40% off the amount of *Nexchange* and an upper limit of *Nimport* of 40 kg N ha^{-1} is imposed, reflecting the restrictions of the considered organic farming associations. In the third scenario, *OrgClo*, the exchange of biomass as fermentation substrate against biogas digestate is permitted, but application of additional *Nimport* is prohibited. This scenario comes closest to a closed N cycle, while marketable products as well as losses continue to export nutrients from the system. Hence, in all scenarios, farms are allowed to exchange biomass for biogas digestate, while the import of additional biogas digestate is restricted depending on the scenario. Costs for transporting fermentation substrate to the biogas plant and biogas digestate back to the farm, as well as for their application, are considered (KTBL 2019a; Strobel 2012). It is assumed that biogas digestates stemming from delivered biomass (*Nexchange*) are provided at no charge. For *Nimport*, costs reflect the value of the nutrients included (Bruns 2022).

Table 4.3 Scenario description

	Conventional	Organic		
	(Conv)	EU regulation (*OrgEU*)	Association [a] (*OrgAss*)	Closed N cycle (*OrgClo*)
Mineral N fertilizer	YES	NO	NO	NO
Nexchange	YES	YES	YES	YES
Nimport	YES	YES	40% of N in exported biomass, max 40 kg ha^{-1}	NO

Notes: [a] Corresponds to the membership in an organic farming association.

4.2.3 Overview of the FarmDyn model

The economic potential of organic farming is assessed using the bio-economic farm scale model FarmDyn. Drawing on farm- and activity-specific differentiated data, FarmDyn offers high detail with regard to farm management and generates a rich set of output indicators, such as for investment performance, factor use and technology adoption. Given its data needs, the model is particularly suitable for case study analyses (Britz et al. 2021a). The study hence gives preference to the depth of analysis over a larger sample size.

FarmDyn is an established model frequently used, for example, for policy assessment (Kuhn et al. 2019), technology adoption (Pahmeyer and Britz 2020) and environmental performance assessment (Heinrichs et al. 2021a). By maximizing the farm`s net present value, the model provides a framework for simulating economically optimal farm-level plans and management decisions under changing boundary conditions, such as policy instruments and new technologies. In this study, a comparative-static version of FarmDyn is used where investment costs in buildings and machinery are annualized. The default data and parameterization include detailed technical data for Germany covering field operations for over a hundred crops, detailed by tillage types, farming system (conventional and organic) and intensity (KTBL 2019a). Machine and labor requirements depend on plot size and farm-plot distance (Heinrichs et al. 2021b). In addition, the model covers detailed data on machinery costs and input requirements and direct costs in crop production (KTBL 2019b). A complete model documentation is available online (Britz et al. 2021b).

Fertilization

Commonly applied methods and data for fertilization planning in farm models are based on conventional farming systems, which are, among others, characterized by high yield levels and high nutrient contents in harvested crops and crop residues (Stein-Bachinger et al. 2004). In organic farming systems, N flows differ considerably from those in conventional systems (Pandey et al. 2018). For example, due to the dominant use of mineral N fertilizers or manure under conventional production, N stemming from legumes is not, or in a simplified way, considered in nutrient accounting (Stein-Bachinger et al. 2004). Therefore, as part of the study, a N fertilization scheme for bio-economic farm models is developed that takes the specifics of organic production into account.

So far, only few methods for nutrient balancing are available that consider organic farming (e.g. Brock et al. 2012; Korsaeth and Eltun 2000; Küstermann et al. 2010; Pandey et al. 2018; van der Burgt et al. 2006). These N management systems aim, for instance, to assess the environmental performance of agroecosystems and provide a better understanding of N dynamics and do not consider all relevant N sources that are required to determine fertilization requirements in bio-economic models, such as soil mineral N (Weckesser et al. 2021). Accordingly, the method developed in the context of the presented work considers all relevant N flows and allows the calculation of fertilization requirements (1) at the level of a single plot, (2) for a variety of crops, (3) under both conventional and organic production (Figure 4.2). In the following section, a brief overview of the approach is given, for details see Appendix 4.C.

$$\begin{aligned} Nneed_c \leq\ & Nfix_c + NfixSelf_{leg} + NminResidues_c + Nseed_c + Nmin_c \\ & + NminVeg_c + NasymFix_c + Ndeposition_c + Nferment_c \\ & - NfermentLoss_c + NminFert_c - NminFertLoss_c - Nleach_c \\ & - Ndenitrification_c - Nsen_c \end{aligned} \tag{1}$$

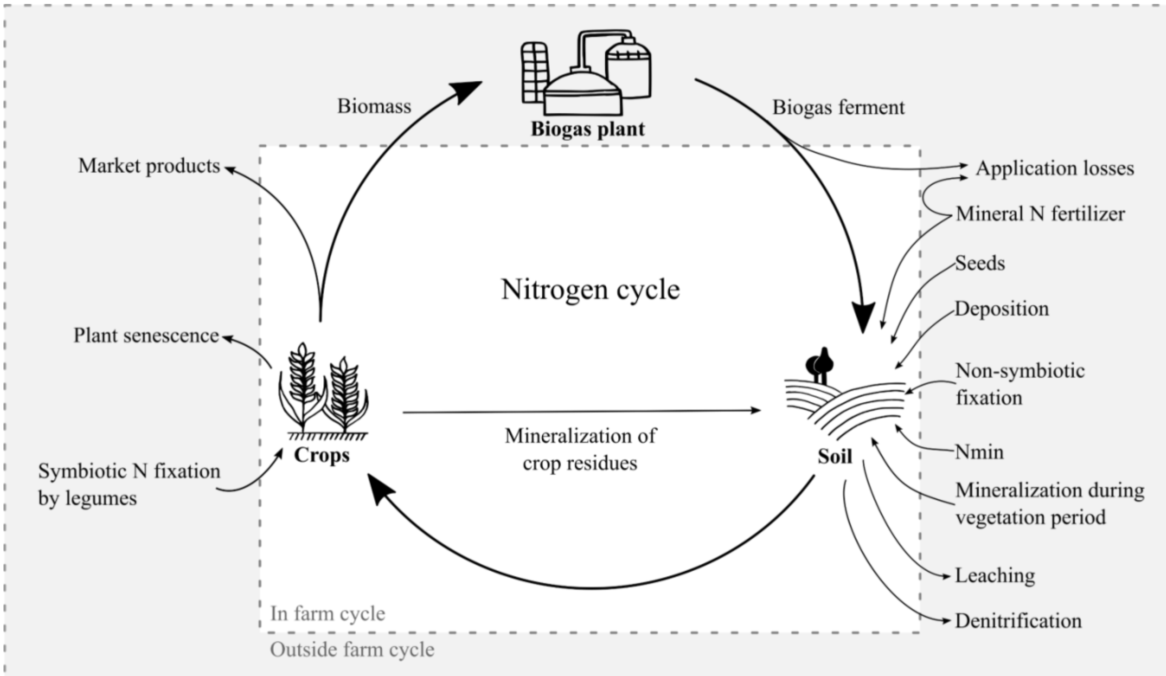

Figure 4.2 Nitrogen (N) cycle of the developed N fertilization scheme

The N requirements $Nneed$ are specified for each crop c and consider N in harvested main and by-products $Nharvest$ and in crop residues $Nresidues$. These N requirements are met considering all relevant N sources and sinks (Eq. 1). Yield levels for all crops are fixed differentiated for conventional and organic farming and the sum of the presented sources needs to provide the required N to achieve given yields. Values calculated both endogenously and exogenously are used for this purpose, based on data from various sources specified in Table 4.4.

Symbiotic N fixation $Nfixation$ of legumes leg are estimated applying a method from Stein-Bachinger et al. (2004), by accounting for the total N content of legumes $Nneed$, the share of N derived from atmosphere $Ndfa$ and the share of legumes L in biomass in case of legume-nonlegume mixtures. The share of $Nfixation$ available to the subsequent crop $Nfix$ considers the amount of N included in the harvested legume $NfixSelf$ and thus, removed from the farm's N cycle. The uptake of N from mineralized crop residues $NminResidues$ is considered applying a method of Stieber (2021). Further N sources include the input of N by seeds $Nseed$, N provided from mineralization in soil in spring $Nmin$ as well as N delivery from soil available to crops during vegetation period and after *Nmin*-sampling $NminVeg$. Non-symbiotic N fixation $NasymFix$ is considered with 5 kg N ha^{-1} (Stein-Bachinger et al. 2004). Wet and dry atmospheric deposition $Ndeposition$ is set to 27.4 kg N ha^{-1} (Gauger 2013). Due to rainfed production only, N inputs from irrigation water are not considered (Sainju 2017).

Table 4.4 Nitrogen (N) sources and sinks included in the N fertilization scheme

Source	Acronym	Unit	References
N requirements			
N demand of harvested main and by-products	$Nharvest$	kg N ha^{-1}	
and non-harvested crop residues	*Nresidues*		
N content in main product, by-product, and residues	*NcontM* *NcontR*	kg N t^{-1}	Bachinger et al. 2015; BMEL 2017; Köhler and Kolbe 2007
Crop yield	*Y*	t ha^{-1}	JKI 2019; KTBL 2019b; Land-Data 2021; Pahmeyer 2021
Ratio main and by-products	α	%	Bachinger et al. 2015; Köhler and Kolbe 2007
Share of by-product sold	β	%	
Quantity of crop residues	*r*	t ha^{-1}	Bachinger et al. 2015
N inputs			
Symbiotic N fixation	*Nfixation*	kg N ha^{-1}	Küstermann et al. 2010; Stein-Bachinger et al. 2004
N content of legumes	*Nneed*	kg N ha^{-1}	Bachinger et al. 2015; BMEL 2017; Köhler and Kolbe 2007
Ndfa (N derived from atmosphere)	*Ndfa*	%	Anglade et al. 2015; Li et al. 2015
Share of legumes	L	%	KTBL 2019b
N mineralization from crop residues	*NminResidues*	kg N ha^{-1}	
N in residues	*Nresidues*	kg N ha^{-1}	
Share of N available to subsequent crop	γ	%	Stieber 2021
N added by crop seed	*Nseeds*	kg N ha^{-1}	
N content in seeds	*NcontSeed*	kg N kg^{-1}	Kolbe and Köhler 2008
Applied quantity	*q*	kg ha^{-1}	KTBL 2019b
Soil mineral N content, spring	*Nmin*	kg N ha^{-1}	LWK NRW 2021
N mineralization, vegetation period	*NminVeg*	kg N ha^{-1}	LTZ 2021
Non-symbiotic N fixation	*NasymFix*	kg N ha^{-1}	Stein-Bachinger et al. 2004
Atmospheric N deposition	*Ndeposition*	kg N ha^{-1}	Gauger 2013
Total mineral N fertilization	*NminFert*	kg N ha^{-1}	
Total N in biogas digestate	*Nferment*	kg N ha^{-1}	
N outputs			
Application losses of synthetic fertilizer and biogas digestate	*NminFertLoss* *NfermentLoss*	kg N ha^{-1}	Haenel et al. 2018; IPCC 2006; Stehfest and Bouwman 2006
N leaching	*Nleach*	kg N ha^{-1}	Richner et al. 2014
Denitrification N loss	*Ndenitrification*	kg N ha^{-1}	Hermsmeyer and van der Ploeg 1996; Stein-Bachinger et al. 2004
N loss at plant senescence	*Nsen*	%	Sainju 2017

Notes: Data used to calculate N requirements of crops as well as N sources and sinks considered to calculate N fertilization requirements, including details on references accessed.

The N requirements of crops can additionally be covered by fertilization. Under organic farming, biogas digestates stemming from fermentation $Nferment$ are the only mobile, N-rich fertilizer. Under conventional production, N requirements can further be covered by the application of mineral N fertilizer $NminFert$. Unavoidable losses that occur during the application of biogas digestates $NfermentLoss$ and synthetic N fertilizer $NminFertLoss$ are considered (IPCC 2006; Haenel et al. 2018; Stehfest and Bouwman 2006). For biogas digestates, further N losses arising during application are taken into account, considering the month and technique of application (Haenel et al. 2018).

N losses through leaching $Nleach$ are estimated based on SALCA-NO3 method by Richner et al. (2014) and depend, for example, on crop types and month of application. Denitrification losses from soil $Ndenitrification$ are considered with 20 kg N ha^{-1} (Hermsmeyer and van der Ploeg 1996; Stein-Bachinger et al. 2004). N losses through plant senescence $Nsen$ are set to 5% of aboveground plant N (Sainju 2017). As N losses through soil erosion and surface runoff in flatland are reported to be small (Sainju 2017), they are not considered. Furthermore, FarmDyn does not cover the soil carbon stock and the carbon-N relation which impact on some N sources.

4.2.4 Modeling setup

Calibration

Using a bi-level estimation approach (Britz 2021), the model is calibrated to crop shares reflecting the crop rotations proposed by the expert panel (Table 4.1). The calibration ensures that the First Order Condition for a profit maximum holds at the respective crop shares, by down- or upward adjusting certain crop specific parameters. During calibration, squared relative deviations from the original parameter values are minimized. The related maximal allowed relative deviations (Appendix 4.D) are generally quite modest, suggesting a plausible structure and original parameterization of the model. The bounds for the objective refer to the optimal profit before calibration. These bounds are manually chosen to arrive at plausible overall farm profits given the originally reported costs and revenue data and crop shares. The organic system is calibrated for the scenario *OrgAss* which reflects the membership in an organic farming association. The expert panel was explicitly advised to define the organic crop shares for this scenario. Accordingly, reported crop share results for the conventional systems and *OrgAss* are calibrated and reflect the opinion of the expert panel. In the other two scenarios, *OrgEU* and *OrgClo*, the crop shares and other farm management options are optimized endogenously by the model to reflect changes in N availability given the calibrated parameters and considering agronomic thresholds and constraints. Other farm management decisions such as machinery, labor or fertilizer use, including potential exchanges with a biogas plant, are endogenously optimized for all scenarios, subject to existing regulations and scenario specific assumptions.

Sensitivity analysis

The analysis is completed by a large-scale sensitivity analysis to quantify the impact of parameters that are subject to large uncertainty. The parameter choice also reflects knowledge on their economic importance. Parameters tested include the distance to biogas plant (0.5 – 50 km), the subsidy granted for organic production (0 – 500 € ha^{-1}), prices and yields of organic products (50% – 150% of implemented parameters), the prices of diesel (0.5 – 3 € l^{-1}) and N fertilizers (50 – 500% of the implemented price of the respective fertilizer), and the soil mineral N content in spring *Nmin* (minimum and maximum values of the past 10 years). Considered ranges reflect plausible maximum and minimum values for each parameter, not necessarily symmetrically distributed around the parameter values implemented in the baseline. An explanation of the parameter selection and the specification of the ranges is given in the Appendix Chapter 4 (Appendix 4.E). For each farm and scenario (see section 4.2.2), 500 samples are randomly drawn from the specified ranges for each parameter. FarmDyn simulates the optimal farm-level plan for each draw by maximizing the net present value. The sampled results feed into a descriptive statistical analysis of the economic potential of each farm and scenario.

4.3 Results

Table 4.5 Economic performance of case study farms

	Conventional	Organic		
	Conv	OrgEU	OrgAss	OrgClo
Farm COP				
Profit (€ ha^{-1})	1,031	1,313 (+27%)	1,188 (+15%)	1,089 (+6%)
Organic subsidy (€ ha^{-1})	-	260	260	260
Profit before organic subsidy (€ ha^{-1})	1,031	1,053 (+2%)	928 (-10%)	829 (-20%)
Revenue (€ ha^{-1})	1,857	1,537 (-17%)	1,418 (-24%)	1,334 (-28%)
Variable costs (€ ha^{-1})	1,049	698 (-33%)	690 (-34%)	693 (-34%)
Labor requirements (h ha^{-1})	29.9	30.8 (+3%)	34.1 (+14%)	36.9 (+23%)
in crop production (h ha^{-1})	12.3	12.1 (-1%)	15.4 (+25%)	18.1 (+47%)
in farm management (h ha^{-1})	17.6	18.7 (+6%)	18.7 (+6%)	18.7 (+6%)
Profit per working hour (€ h^{-1})	34.5	42.6 (+23%)	34.8 (+1%)	29.6 (-14%)
Total N applied[1] (kg ha^{-1})	161	39.1 (-76%)	38.3 (-76%)	36.6 (-77%)
N input (kg ha^{-1})	161	24.6 (-85%)	11.0 (-93%)	0 (-100%)
N exchanged (kg ha^{-1})	0	14.5	27.4	36.6
Farm COP+R				
Profit (€ ha^{-1})	1,522	1,907 (+25%)	1,721 (+13%)	1,590 (+4%)
Organic subsidy (€ ha^{-1})	-	260	260	260
Profit before organic subsidy (€ ha^{-1})	1,522	1,647 (+8%)	1,461 (-4%)	1,330 -13%)
Revenue (€ ha^{-1})	2,836	2,596 (-8%)	2,374 (-16%)	2,205 (-22%)
Variable costs (€ ha^{-1})	1,262	968 (-23%)	934 (-26%)	895 (-29%)
Labor requirements (h ha^{-1})	23.6	19.2 (-19%)	19.8 (-16%)	20.1 (-15%)
in crop production (h ha^{-1})	15.4	10.5 (-32%)	11.0 (-28%)	11.3 (-26%)
in farm management (h ha^{-1})	8.2	8.8 (+7%)	8.8 (+7%)	8.8 (+7%)
Profit per working hour (€ h^{-1})	64.5	99.3 (+54%)	87.1 (+35%)	79.2 (+23%)
Total N applied[1] (kg ha^{-1})	167	61.2 (-63%)	57.9 (-65%)	55.3 (-67%)
N input (kg ha^{-1})	167	41.5 (-75%)	16.5 (-90%)	0 (-100%)
N exchanged (kg ha^{-1})	0	19.7	41.4	55.3
Farm COM				
Profit (€ ha^{-1})	1,379	2,059 (+49%)	1,839 (+33%)	1,737 (+26%)
Organic subsidy (€ ha^{-1})	-	260	260	260
Profit before organic subsidy (€ ha^{-1})	1,379	1,798 (+30%)	1,578 (+14%)	1,477 (+7%)
Revenue (€ ha^{-1})	2,675	3,031 (+13%)	2,805 (+5%)	2,707 (+1%)
Variable costs (€ ha^{-1})	1,255	1,216 (-3%)	1,193 (-5%)	1,185 (-6%)
Labor requirements (h ha^{-1})	32.4	37.3 (+15%)	40.9 (+26%)	43.9 (+35%)
in crop production (h ha^{-1})	17.4	21.3 (+22%)	24.9 (+43%)	27.9 (+61%)
in farm management (h ha^{-1})	15.1	16.0 (+6%)	16.0 (+6%)	16.0 (+6%)
Profit per working hour (€ h^{-1})	42.5	55.2 (+30%)	44.9 (+6%)	39.5 (-7%)
Total N applied[1] (kg ha^{-1})	155	48.8 (-68%)	44.8 (-71%)	35.6 (-77%)
N input (kg ha^{-1})	155	39.1 (-75%)	12.8 (-92%)	0 (-100%)
N exchanged (kg ha^{-1})	0	9.7	32.0	35.6

Notes: [1] N from fertilizers and fermentation substrates. The acronyms correspond to Farm COP: Specialist cereals, oilseeds, protein crops; Farm COP+R: Cereals, oilseeds, protein crops and *root crops combined; Farm COM: Various field crops combined; Conv: Conventional production; OrgEU: Organic production according to EU regulation; OrgAss: Organic production according to regulation of private farming association; OrgClo: Organic production with closed nitrogen (N) cycle.*

4.3.1 Conventional farming

Comparing the economic performance of the three case study farms under conventional production, profits are lowest on farm COP (1,031 € ha^{-1}), along with the lowest revenues (1,857 € ha^{-1}) and variable costs (1,049 € ha^{-1}) (Table 4.5). The farms COP+R and COM generate higher profits (1,522 and 1,379 € ha^{-1}). Here, higher revenues (2,836 and 2,675 € ha^{-1}), mainly due to root crop production, compensate for higher variable costs (1,262 and 1,255 € ha^{-1}). The conventional crop rotations, characterized by the intensive production of cash crops, require large amounts of N, with off-farm N applied varying between 155 and 167 kg N ha^{-1}. Each farm produces winter cereals and grain maize, while winter rape is grown on farms COP and COP+R, potatoes and sugar beets are produced on farms COP+R and COM (Figure 4.4). Catch crops and idle land are used to fulfill the ecological focus area obligations under the Common Agricultural Policy. Labor demand varies between 23.6 and 32.4 h ha^{-1} reflecting two main drivers. First, labor inputs increase with higher shares of potatoes in the crop rotation which require considerably more labor than other crops. Second, per hectare labor inputs decrease with farm size, reflecting that labor requirements of tasks that are in large parts independent of farm size, such as farm management, are distributed over a larger area. Consequently, the labor productivity of the farms differs considerably and varies between 34.5 and 64.5 € h^{-1}, being highest for farm COM and lowest for farm COP.

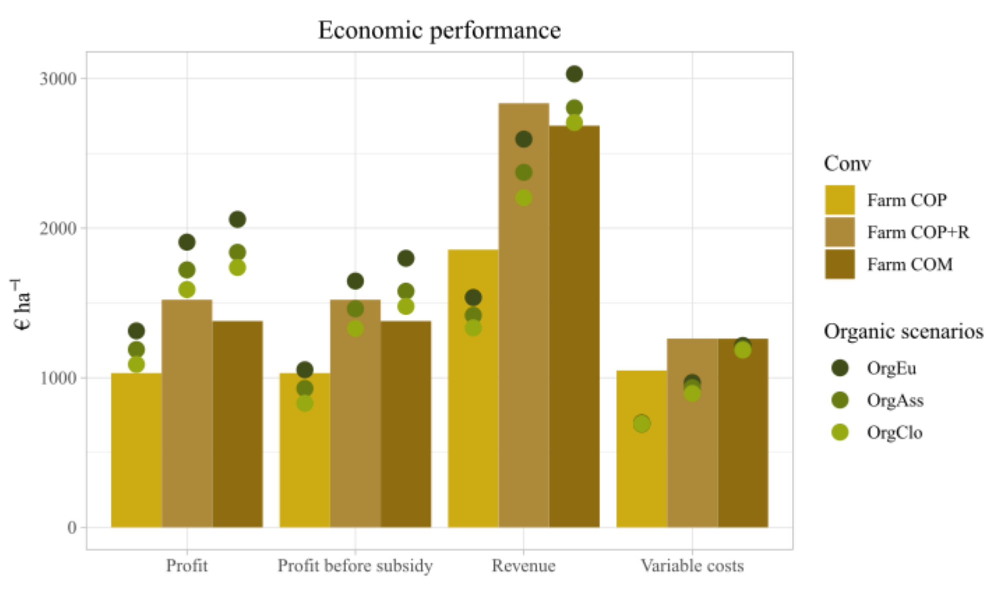

Figure 4.3 Economic performance of case study farms under conventional and organic production

Notes: Farm COP: farm type 151: specialist cereals, oilseeds, protein crops; farm COP+R: farm type 162: cereals, oilseeds, protein crops and root crops combined; farm COM: farm type 166: various field crops combined; Conv: conventional production; OrgEU: organic production according to EU regulation; OrgAss: organic production according to regulation of private farming association; OrgClo: organic production with closed N cycle.

4.3.2 Organic farming

According to the results of the expert panel, the production of grain maize and winter grains is reduced in organic farming, and partly replaced by summer grains, with wheat and barley being supplemented by oats and spelt. Farm COP slightly reduces its rapeseed production under organic farming, while it is dropped in farm COP+R. Here, sugar beet production is further abandoned due to a lack of marketing options. Potato production slightly decreases on farm COP+R, while it is somewhat expanded on farm COM.

Organic farming is the more profitable system for the three farms in all assessed scenarios when subsidies granted for organic production are considered (Figure 4.3). However, the share of the increase in profits that is attributable to subsidies for organic production varies widely, and without these subsidies, profits fall in some cases below the level of conventional production. These cases are found under stricter regulations on the import of off-farm N, which considerably decreases the profitability of organic farming. The profit loss is mainly due to a decrease in revenues induced by required adjustments in crop shares when less N is available at farm level, while variable costs are less volatile. Labor requirements in crop production are affected differently by the adjustments on each farm. Overall, labor requirements increase in the more restrictive scenarios, caused by an increased production of crops with higher labor demand, such as clover-grass. The labor demand for farm management increases between +6% and +7% under organic production on all three farms, independent of the scenario.

OrgEU

The possibility to import off-farm N without being obliged to export fermentation substrate in *OrgEU* implies that legumes are not required as a source of N. However, legumes are grown up to the assumed required minimum share of 25% in organic crop rotations in all farms, as indicated by the export panel and literature (Kempkens et al. 2013; Kolbe 2008). Due to their marketing potential, grain legumes are preferred over fodder legumes, and complemented by clover-grass. Besides lower N crop needs due to reduced yields, the still high share of legumes and the exchange of the total amount of clover-grass for biogas digestate reduce the amount of both total N applied and off-farm N compared to conventional production. The amount of N applied is on average reduced by -69% to 39.1 to 61.2 kg N ha^{-1}. Thereof, 32% stems from the exchange of clover-grass for biogas digestate. The availability of N from legume fixation as well as the possibility to import biogas digestates allows the cultivation of crops which require larger amounts of N. Potatoes on farm COP+R and COM as well as rapeseed on farm COP are grown at their maximum crop rotational share, while cereal production focuses on wheat and grain maize production.

On farm COP and COP+R, revenues decrease under organic production by -17% and -8% to 1,537 and 2,596 € ha^{-1}, respectively (Table 4.5). Here, higher prices for organic products cannot outweigh lower yield levels and the smaller share of cash crops in the organic crop rotations. On farm COM, revenues increase by +13% to 3,031 € ha^{-1}, mostly due to a higher share of potatoes compared to the conventional crop rotation. Variable costs are lower under organic production, mainly due to lower expenses for pesticides and fertilizers. Profits increase for all farms, by +27% (+282 € ha^{-1}) for farm COP, by +25% (+385 € ha^{-1}) for farm COP+R, and by +49% (+680 € ha^{-1}) for farm COM. This is mainly due to subsidies for organic farming, accounting for 92%, 68% and 38% of the additional profit, but also to reduced variable costs by -33%, -23% and -3%, respectively. Even if subsidies granted to organic production are not considered, organic farming is the profit maximizing farming system for all farms under this scenario. As expected, the differences in profits decline considerably to +2% (+22 € ha^{-1}) for farm COP, +8% (+125 € ha^{-1}) for farm COP+R and +30% (+419 € ha^{-1}) for farm COM.

Effects on total labor requirements are not conclusive. On farm COP+R, despite the increase in labor demand for farm management, total labor requirements fall below the conventional level (-19%), driven by a decrease in labor demand for crop production (-32%). This is partly due to the lower share of crops with high labor demand, such as potatoes. Furthermore, the per hectare labor demand for certain crops decreases in organic farming due to fewer machine passes over the field, and the contracting out of substrate fertilization, whereas chemical fertilizer application is assumed to be handled by the farm itself. In contrast, the demand for labor of farm COP and farm COM increases by +3% and +15%, respectively. In farm COP, this is due to the increase in labor demand in farm management, while labor requirements in crop production remain almost constant (-1%). In farm COM, an increase in labor requirements in crop production (+22%) is due to the rising share of crops with relatively high labor demand, such as clover-grass and soybeans (Figure 4.4). Overall, the total labor productivity increases for all farms (+23% for farm COP, +54% for farm COP+R, +30% for farm COM), reflecting the considerable profit difference to the conventional system.

OrgAss

Restricting the import of biogas digestates to 40% and to a maximum of 40 kg N ha^{-1} in addition to the amount of N included in the exported biomass (*OrgAss*) decreases the economic potential of organic farming. The shares of legumes of about one third indicated by the expert panel are higher compared to *OrgEU* and are required to offset the more limited import of off-farm N. Again, the entire amount of clover-grass biomass is exchanged for biogas digestate. Compared to conventional production, the total amount of N applied is on average reduced by 71% to between 38.3 and 57.9 kg N ha^{-1}, while the share of *Nexchange* increases to about 71%. The limited availability of N compared to *OrgEU* implies less production of crops with high N fertilizer requirements, as stated by the expert panel. For example, barley partially replaces wheat cultivation while potatoes continue to be grown at the farm-specific maximum rotational share, reflecting their high profitability. These changes in crop rotations result in a lower share of economically valuable crops, and thus in a decrease in revenues, reaching 1,418 € ha^{-1} in farm COP (-24% in comparison to conventional farming), 2,374 € ha^{-1} in farm COP+R (-16%) and 2,805 € ha^{-1} in farm COM (+5%). In contrast, variable costs remain mostly unaffected. Hence, the profits decrease compared to *OrgEU*, however, they remain above the conventional profits for all study farms: +157 € ha^{-1} (+15%) for farm COP, +199 € ha^{-1} (+13%) for farm COP+R and +459 € ha^{-1} (+33%) for farm COM. The difference in profits to conventional farming on farm COP and COP+R is now entirely due to the organic subsidy, while it covers 57% of the profit difference on farm COM. Thus, if organic subsidies are not considered, the profitability of farms COP and COP+R is lower under organic production with -103 € ha^{-1} (-10%) and -61 € ha^{-1} (-4%), while it remains the profit-maximizing farming system for farm COM with +199 € ha^{-1} (+14%). The labor demand of all three farms increases compared to *OrgEU*, caused by the increased production of crops with higher labor requirements, such as clover-grass and grain maize. Compared to conventional production, total labor input remains, however, lower on farm COP+R (-16%), while labor inputs are higher on farms COP and COM, at +14% and +26%. In all three farms, the restriction on N import causes labor productivity to considerably decrease compared to *OrgEU*. Nevertheless, it remains higher than under conventional production: +1% for farm COP, +35% for farm COP+R, and +6% for farm COM.

OrgClo

Without the possibility to import any biogas digestate in addition to the amount of N included in the exported biomass (*OrgClo*), the economic potential of organic farming further decreases. The limited availability of N results in a further increase in legume production, reaching shares of 37% to 39%. The amount of N applied is further reduced compared to conventional production, by -73% on average. The total amount of N stems from the exchange of biomass for biogas digestate, according to the scenario assumption. The crop rotation further shifts to crops exhibiting lower N fertilization requirements, such as summer barley, while rapeseed and potato production remain constant and cover the maximum rotational share of the respective farms (Figure 4.4). Changes in crop rotation result in a further decline in revenues, being -28%, -22% and +1% of conventional revenues for farms COP, COP+R and COM, respectively, while variable costs remain almost unchanged. If subsidies granted to organic production are considered, conversion to organic farming remains, however, the profit increasing option for all farms: +58 € ha^{-1} (+6%) on farm COP, +68 € ha^{-1} (+4%) on farm COP+R and +358 € ha^{-1} (+26%) for farm COM. At farm COM, the share of subsidies in profit difference increases to 73%, while subsidies continue to account for the entire profit difference at the other farms. Excluding subsidies, organic farming is thus less profitable on farm COP and COP+R with -202 € ha^{-1} (-20%) and -192 € ha^{-1} (-13%), while it still generates higher profits on farm COM with +97 € ha^{-1} (+7%) (Table 4.5). Total labor requirements further increase, reaching +23%, -15% and +35% of conventional labor demand for farm COP, COP+R and COM, respectively. Rising labor requirements combined with declining profits lead to a further decrease in labor productivity, with farm COP and COM falling -14% and -7% below conventional production levels, respectively.

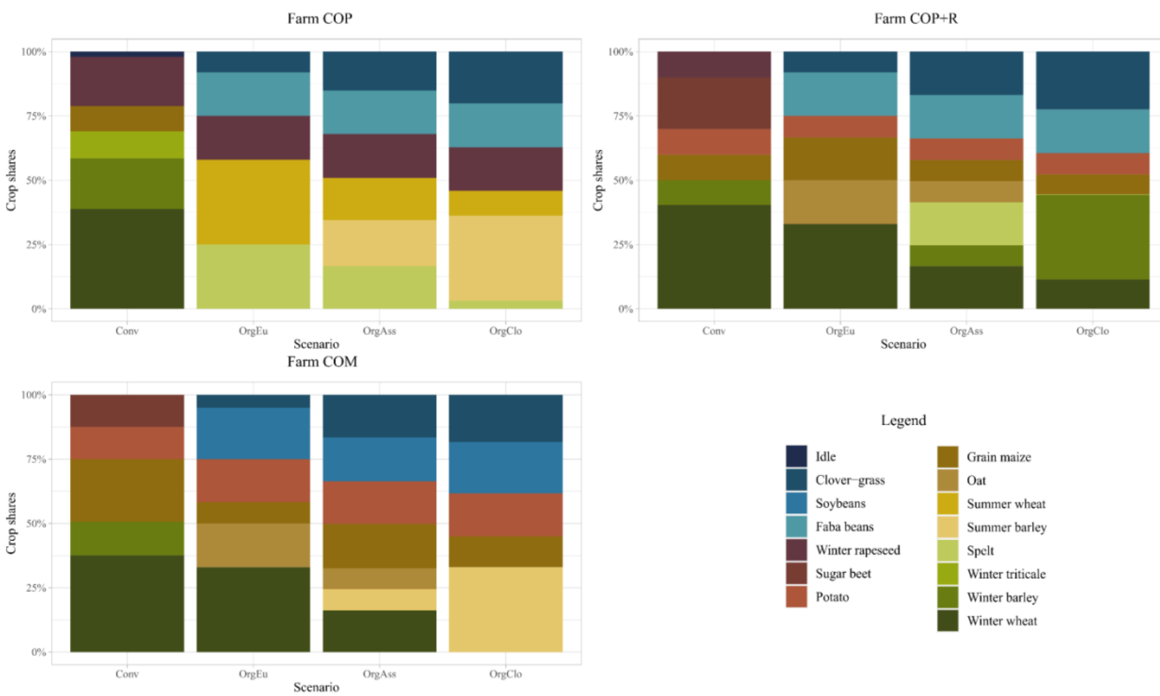

Figure 4.4 Changes in crop shares of the case study farms

Notes: The crop rotations for conventional farming and the scenario OrgAss are result of the structured survey of the expert panel. The crop shares of the scenarios OrgEU and OrgClo show adjustments reflecting changes in N availability given the calibrated parameters and considering agronomic threshold and constraints. Farm COP: farm type 151: specialist cereals, oilseeds, protein crops; farm COP+R: farm type 162: cereals, oilseeds, protein crops and root crops combined; farm COM: farm type 166: various field crops combined; Conv: conventional production; OrgEU: organic production according to EU regulation; OrgAss: organic production according to regulation of private farming association; OrgClo: organic production with closed N cycle.

4.3.3 Sensitivity analysis

The results of the sensitivity analysis of farm COP as well as selected results of farm COM are presented in Figure 4.5. As the results of farm COP are largely similar to farm

COP+R, the latter are shown in Appendix Chapter 4 (Appendix 4.F) along with complete results of farm COM.

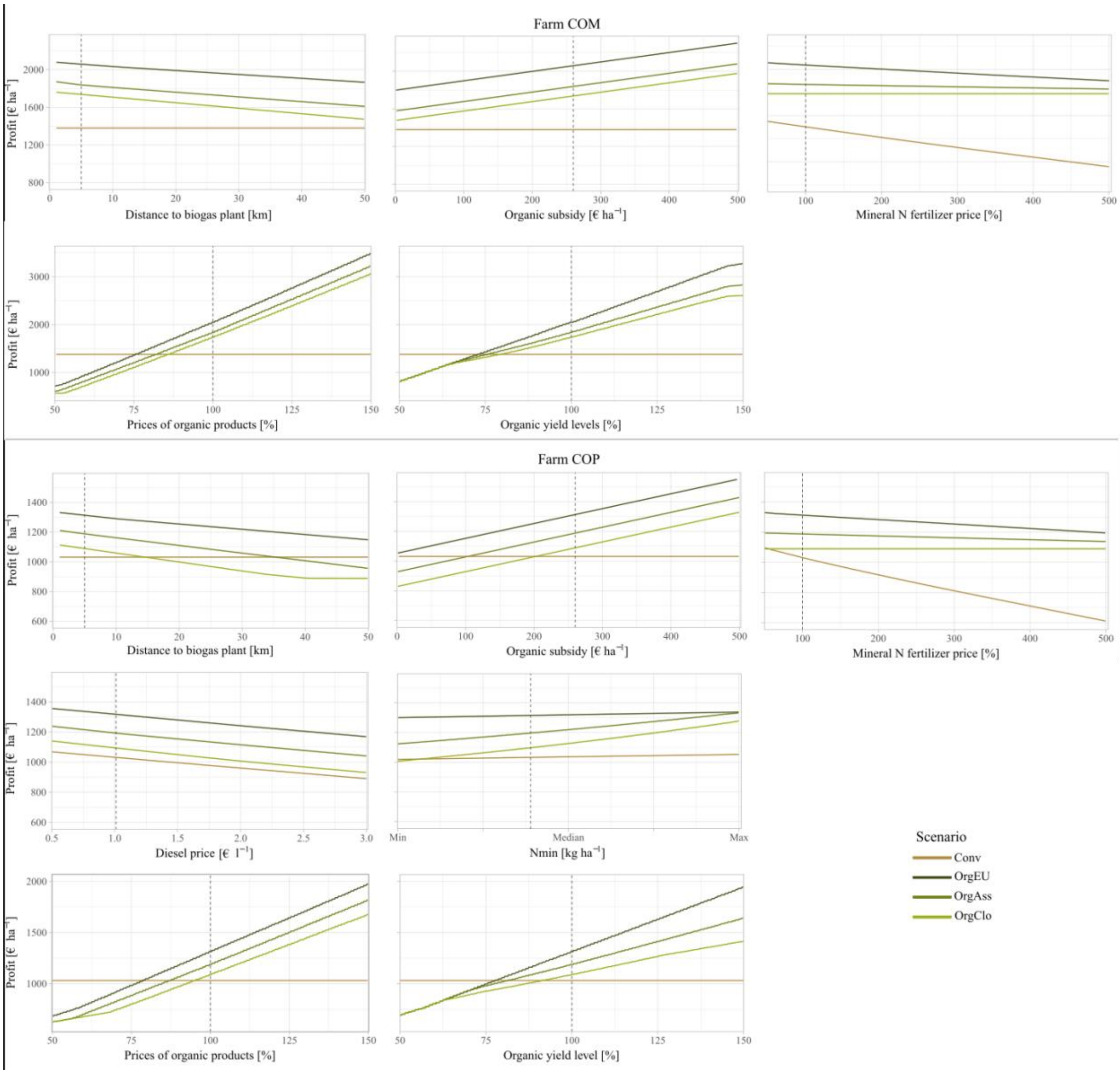

Figure 4.5 Results of the sensitivity analysis

Notes: The dashed lines show the parameter values implemented in the baseline. The implemented mean values of Nmin vary for each crop. Here, the dashed line represents the mean value as average over all crops in the conventional and organic crop rotation. The y-axis scales differ as specified. Farm COP: farm type 151: specialist cereals, oilseeds, protein crops; farm COM: farm type 166: various field crops combined; Conv: conventional production; OrgEU: organic production according to EU regulation; OrgAss: organic production according to regulation of private farming association; OrgClo: organic production with closed N cycle. Nmin: Soil mineral N content in spring.

Distance to biogas plant

An increasing distance to the external biogas plant implies higher transportation costs both for the substrate delivered and the biogas digestate taken back. This can decrease the profitability of organic farming considerably. Impacts are strongest in the *OrgClo* followed by the *OrgAss* scenario where the farms do not only rely on the import of biogas digestates, but also on the export of fermentation substrate. Conventional profits are unaffected by changes in distances as the case study farms apply mineral fertilizer only, such that no biogas digestate is imported. For farm COP and COP+R, conventional farming is more profitable once the distance to the biogas plant exceeds 15 km (30 km) and 12 km (30 km) in the *OrgClo* (*OrgAss*) scenario, respectively. For all farms in the *OrgEU* scenario as well as for farm COM in all scenarios, the profitability of organic farming exceeds the one of conventional farming for all distances considered (0.5 - 50 km).

Organic subsidy

Subsidies granted for organic production contribute to a large extent to the profitability of organic farming and, thus, affect its economic potential considerably. The size of this effect is the same for all organic scenarios. On farm COP and COP+R, *OrgClo* and *OrgAss* are more profitable than conventional farming when subsidies exceed 202 (103) € ha^{-1} and 192 (61) € ha^{-1}, respectively. For farm COM, organic farming is the profit maximizing farming system even without subsidies.

Prices and yields of organic products

Fluctuations in prices and yields of organic products have a major impact on the economic potential of organic farming. In the *OrgAss* scenario, reductions in prices of -5% on farm COP and COP+R and -15% on farm COM cause the profits of organic and conventional farming to converge, while in the *OrgEU* scenario organic farming is more profitable even with price reductions of -17% on farm COP+R to -25% on farm COM.

Yield reductions of -5% (farm COP+R) to -22% (farm COM) lead to a convergence of organic and conventional profits in the *OrgAss* scenario. In the *OrgEU* scenario, organic farming is more profitable even with yield reductions between -19% (farm COP+R) and -27% (farm COM). The effect on profits of increasing yields is stronger for the *OrgEU* scenario as the farms can better respond to the increasing N demand associated with increasing yields.

Diesel and N fertilizer price

Diesel prices, including ranges not yet observed (0.5 - 3 € l^{-1}), affect the profitability of conventional and organic farming systems of the three farms almost equally and thus have no impact on the economic potential of organic farming. In contrast, N fertilizer prices strongly impact the profitability of conventional farming systems, while the effect on organic profits is limited and depends on the scenario. Conventional profits benefit from lower fertilizer prices, while the economic potential of organic farming systems increases as prices rise. Nevertheless, increasing costs for *Nimport* reduce mainly the profitability of the *OrgEU* scenario, however, impacts are limited. As no off-farm N imports are allowed under the *OrgClo*, the farm's profit in this scenario remains unaffected. At low fertilizer prices, the profitability of conventional farming in farm COP and COP+R increases to the point where they reach the level of *OrgClo*. In contrast, the conventional profits of farm COM remain lower than organic profits, regardless of fertilizer prices.

Nmin

Changes in $Nmin$ affect the profits of organic farming considerably, in particular in *OrgClo* and, to a lesser extent, in *OrgAss*. Here, the restricted access to off-farm N increases the importance of $Nmin$ as a source of N input and lower $Nmin$ contents require adaptations of the crop rotation. Due to the option of importing off-farm N, the importance of $Nmin$ decreases in *OrgEU* and almost vanishes under conventional production, such that profits remain almost unaffected. Overall, low $Nmin$ contents decrease the profitability of organic farming. On farm COP and COP+R, minimum $Nmin$ levels lead to a convergence of profits in *OrgClo* and conventional production. As $Nmin$ values increase, the economic potential of organic farming rises. The differences between the organic scenarios become smaller as profits increase, particularly sharply in *OrgClo* and *OrgAss*. At maximum $Nmin$ values, profits of farm COP in *OrgAss* even reach the same level as in *OrgEU*.

4.4 Discussion

4.4.1 Economic performance of conventional and organic production

The results of the study indicate that stockless organic production based on importing biogas digestate is associated with high economic potential for arable farms. However, profitability strongly depends on regulation-specific restrictions on importing off-farm N. The results go beyond existing research focusing on the introduction of biogas digestate on stockless farms which are already managed organically (Blumenstein et al. 2017; Blumenstein et al. 2020; Brock et al. 2017; Serdjuk et al. 2018). These studies did not consider different regulations on the use of off-farm N, nor did they assess the impact on the economic potential of organic farming for so-far conventional arable farms.

This said, our results are consistent with previous findings that suggesting stockless organic production to be associated with higher profits for conventional arable farms (Ács et al. 2007; Taube et al. 2005). We identify three main drivers for higher profits which are in line with literature. First, profit increases reflect price premiums as shown by Nemes (2009), Nieberg and Offermann (2003) and Taube et al. (2005). Second, organic farming is associated with lower costs in crop production, mostly from reduced direct costs and a lower number of passes over the field with consequences on machinery requirements. Similarly, Mahoney et al. (2007) and Nemes (2009) emphasize the lower production costs in organic crop production. Third, higher profits in our study depend to a larger extent on subsidies granted to organic production. Without subsidies, organic farming is not always associated with an increase in profits. Similarly, previous studies underline the relevance of subsidies for the comparative economic advantage of organic production (Brožová and Vaněk 2013; Taube et al. 2005; Nieberg and Offermann 2003).

Our study does not find unidirectional impacts of stockless conversion on labor demand. While labor requirements of organic crop production are lower for most crops, the often necessary switch to a more diversified crop rotation can also introduce more labor-intensive crops or increase their share. Similar to previous research (Offermann and Nieberg 2000), this is here observed for farms COP and COM. Likewise, results of Heinrichs et al. (2021b) and Taube et al. (2005) emphasize the important impact of changes in crop rotation on labor requirements. Additionally, higher labor requirements in farm management of organic farming provoke higher total labor requirements for two farms. The study underlines that labor demand changes due to conversion are heterogenous, reflecting specific crop changes. Our findings, thus, only partially confirm results of previous research that organic arable farms are generally managed more labor intensive (Orsini et al. 2018; Reissig et al. 2016). Likewise, results on labor productivity are mixed, reinforcing claims of Orsini et al. (2018) that the common belief about lower labor efficiency in organic farming is not necessarily valid.

4.4.2 Method and limitations

As part of the study, a N balancing method is developed that reflects specifics of organic production and is suitable for bio-economic farm models. So far, only few methods for N balancing are available that consider organic farming (e.g. Korsaeth and Eltun 2000; Küstermann et al. 2010; Pandey et al. 2018; van der Burgt et al. 2006). These N management systems aim, for instance, to assess the environmental performance of agroecosystems, provide a better understanding of N dynamics and N cycles, and offer support for decision-making and management (Weckesser et al. 2021). Determining fertilization requirements in economic optimization models, however, requires consideration of other N sources and differs in the level of detail of data requirements. In FarmDyn, detailed and dynamic N fluxes can only be modeled in combination with other models, such as site-specific plant-growth models and require large data input. Hence, climate aspects such as temperature and precipitation, as well as agronomic considerations (e.g., which crops follow each other) and the temporal availability of different N sources, are currently not or only static considered. Instead, the method is based on simplified N fluxes and pools using average parameterization from existing data and literature, which might be subject to uncertainties and fluctuations. This increases the applicability and adaptability of the method and allows the analysis of large numbers of farms, for example in policy impact assessment and analysis of the effects of management changes in arable systems. A comparison of the computed N inputs with published values suggests the validity of the new method. The average of 161 kg N ha^{-1} of total N applied under conventional production across the representative case study farms is in line with observations of the German Environmental Agency (2022), which reports average amounts of N input, including deposition, of 188 kg N ha^{-1} between 1990 and 2020. Under organic production, merely 46 kg N ha^{-1} from biogas digestates are applied on average across the farms and scenarios. This fits Kolbe (2015) who reports manure application rates of 42 N ha^{-1} for organic farms in Germany. However, employed mean parameters are subject to uncertainties and natural fluctuations. The sensitivity analysis on $Nmin$ reveals that especially results under the more constrained organic scenarios *OrgAss* and *OrgClo* are affected by variations in the parameterization.

Generally, bio-economic farm scale models are highly suitable for assessing changes in farm management, as they depict in detail bio-physical processes and economic flows, as well as their trade-offs. FarmDyn is a particularly detailed model that includes multiple farm types and over hundreds of crops under conventional and organic production. The new fertilization method added to the model allows for improved analysis and comparison of organic and conventional farming systems, for instance, under changing nutrient regulations. However, yield levels of conventional and organic farming are fixed in our analysis and endogenous adjustments of yields are not possible. An extension of the N balancing method by an N-response curve would be desirable to allow for endogenous adjustments of yields. Bio-economic farm models are principally well suited to strongly differentiate cropping activities depending on N availability and management (Kuhn et al. 2020). The required data, however, are not available for such a large number of crops in different production systems found in the model. In addition, FarmDyn does not yet cover the soil carbon stock and carbon-N relations, which strongly impacts the availability of N, nor does it capture the plant availability of different N compounds. Extending the modeling approach in this respect would allow better depiction of the N available for plant growth and the different characteristics of N fertilizers. N is considered one of the most important yield-determining factors in crop production (Küstermann et al. 2010). However, N oriented yield projections are always subject to uncertainty, among others due to the fact that the yield level is also influenced by other factors and nutrients. These are so far not or, in the case of phosphate, only simplified covered by FarmDyn and pose further risk to yields. In this context, the sensitivity analysis provides meaningful insights into the economic potential of organic production under varying yield levels.

Attention should be paid to the fact that conversion to organic farming is a farm-specific decision governed by on- and off-farm conditions, such that no generally applicable conversion process can be presented. Nevertheless, the organic crop rotations outlined in this study are based on knowledge and experience of a panel of experts for conversion to organic farming in NRW as well as agronomic thresholds from science and field practice, ensuring that our results provide meaningful insights. It should be noted that the assumed minimum rotational share of legumes of 25% under organic production became binding in the *OrgEU* scenario for all three farms. No such mandatory limit exists in the EU regulation and lower legumes shares are partly observed on organic farms (Kolbe 2015). Despite this, in line with the expert panel, we consider this limit as plausible as lower legume shares are considered unsustainable and unfeasible in the long term for agronomic reasons, such as for weed suppression, soil fertility and loosening (Kempkens et al. 2013; Kolbe 2008). However, our approach does not allow us to quantify and thus consider long-term benefits of especially fodder legumes. This likely leads to an underestimation of the economic performance of legumes in our results. This study focuses on the interaction of organic farms with external biogas plants. Therefore, clover-grass harvesting is considered as the only management option while other options, such as mulching, are excluded from the analysis. This provides multiple positive impacts, such as on soil fertility, crop yields and quality, while reducing environmental impacts and increasing N-fixation capacity (Hofmann et al. 2015; Loges and Heuwinkel 2004; Möller et al. 2006; Stinner et al. 2008).This study is based on statistically representative conventional case study farms. By choosing NRW as a case study region, we study conversion in an intensive productive area where favorable production possibilities drive opportunity costs of conversion. Our study shows that high economic potential for organic farming can be achieved on productive sites through cooperation with a biogas plant. Thereby, the economic performance of stockless organic farming strongly depends on the import opportunities of nutrients. Cooperation with a biogas plant can thus drive the conversion of arable farms, where it is costly. A larger sample, covering more heterogeneous farm types and production programs, is required to generalize our findings and identify further drivers of performance and obstacles of conversion. Analysis at the level of a farm population is hampered by important data limitations. Generally, available databases do not cover organic farming well (Kerselaers et al. 2007). Specifically, stockless organic production is a rather recent trend (Taramarcaz and Clerc 2013) such that observations before and after conversion are quite scarce in existing single farm records, such as the Farm Accountancy Data Network (FADN). Moreover, the analysis requires information on the cooperation with external biogas plants and data on the import off-farm N, which are currently not part of official statistics. Extending research to larger samples hence requires either collection of primary data by dedicated studies or changes in statistical data coverage. Still, our results underline clearly that the cooperation with an external biogas plant to import of off-farm N can support the conversion of specialized arable farms. Our large-scale sensitivity analysis delivers results beyond the current and regional specific economic contexts. These render the results of interest beyond NRW, as many countries aim at increasing the share of organically managed farmland, while specialized arable farms lag behind in conversion.

Comparing the profitability before and after conversion requires either observations or, as in our case, the use of normative models. Normative models represent a valuable tool to provide ex-ante insights and allow for a profound analysis of changes in performance indicators associated with the conversion to organic farming. As many other such models, FarmDyn is largely based on available data, such as costs, yields, and labor and machinery needs, which refer to averages and are known to differ among farms. For instance, higher profits in organic farming largely reflect price premiums, which depend on access to organic value chains and the general development of the demand for organic products. Furthermore, price premiums may even decline in the future due to market saturation effects. Our sensitivity analysis shows that price drops for organic products strongly reduce the economic potential of organic farming. Farm models as supply side models are not able to quantify such market feedback and give estimation of price changes due to increased conversion to organic farming. Further, for our study, we had to assume the same premiums in all three scenarios, as price statistics do not distinguish between organic products according to regulations of the EU or organic farming associations. Additional economic incentives not covered by the analysis, such as higher price premiums or improved market access, associated with the membership in an organic farming association, might narrow the differences in economic performance between the scenarios.

The study focuses on economic performance indicators. Even though economic considerations gain importance for the decision to convert to organic farming (Flaten et al. 2006; Läpple and van Rensburg 2011; Łuczka and Kalinowski 2020; Lund et al. 2002), it is found to depend on further factors (Koesling et al. 2008; Läpple and Kelley 2013; Xu et al. 2018). Against this background, our results should not be understood as adoption predictions but improve the understanding of the economics of conversion and allow for a more targeted promotion of organic farming systems.

4.5 Conclusion

This study assesses the economic potential of organic production for specialized arable farms. It examines the impacts of different regulations on importing off-farm biogas digestates on the economic performance of organic farming. Our results indicate that the use of biogas digestate renders stockless conversion of specialized arable farming profitable under current market and policy conditions in Germany. Stronger restrictions on the import of off-farm N, as set by organic farming organizations, shift crop rotation toward less profitable crops.

Our study underlines that the economic potential of stockless organic farming depends highly on import possibilities of nutrients. Nutrient flows from conventional agriculture, such as here via biogas digestates, allow to overcome this barrier and to expand and intensify organic production. This supports reaching existing policy goals related to organic production and reduces pressures from nutrient surpluses in conventional systems. However, intensified use of nutrients from external and especially conventional sources violates a closed nutrient cycle as a core concept of organic farming. Given the export of nutrients through market products and unavoidable losses, particularly on stockless farms without farmyard manure, all measures to maintain soil fertility and nutrient supply should be exploited to limit the import of off-farm nutrients, for example through the cultivation of legumes and the optimal use of available resources. The non-compliance of this concept can negatively impact customer perceptions and threatens the credibility of organic agriculture (Blumenstein et al. 2014), leading to increasing criticism (Deumilch et al. 2016). Generally, the question arises if large imports of organic nutrients diminish the environmental benefits of organic farming. Thus, while the lower barriers for N imports as in the EU regulation could foster conversion, stricter regulations are more consistent with the traditional idea of organic farming and might increase credibility, maintain price premiums and provide environmental benefits. Stakeholders from politics and organic farming organizations need to consider these trade-offs when designing regulations and rules.

Our study focuses on the cooperation of stockless organic farms with conventional biogas plants. Despite a large potential (Hofmann et al. 2015), biogas plants managed by organic farms are rare and cover <2% of all biogas plants (Siegmeier and Blumenstein 2017). Restricting the cooperation to organically managed biogas plants, which is not required by any of the considered regulations, would imply longer transport distances. Our results further suggest that longer distances have a large impact on profitability and thus may reduce the incentive to convert. The fermentation of substrates from organic production in organically managed biogas plants could, however, reduce the dependence of organic farms on conventional nutrients while at the same time contributing to the target of an increased biogas production in organic farming systems (Hofmann et al. 2015). In addition, the cooperation with exclusively organically operated biogas plants excludes the risk of contamination associated with the co-digestion of conventional substrates, such as pesticide and antibiotic residues (Hofmann et al. 2015; Lukehurst et al. 2010). Stricter regulations on substrates, as established by organic farming associations (for example Bioland e.V. 2022) can prevent adverse effects on biology and quality of the soil and ensure the safety and value of the biogas digestates.

The provision of conventional biogas digestate to stockless organic farms adds another valuable dimension to biogas production in the agricultural system. In addition, organic substrates can help to diversify biogas substrates and, thus, increase the sustainability of conventional biogas plants. In Germany, the boost and following slowdown in the emergence of agricultural biogas plants is largely driven by the subsidy policy of the German Renewable

Energy Act. Decisions on biogas support are largely caused by the needs and nature of the energy market, such as current cost differences to other renewable energy sources. When deciding on future funding for conventional and even organic biogas plants, policy makers need to consider the whole range of potential advantages and drawbacks of biogas production, to which the cooperation with organic farms only contributes.

Finally, our findings underline that subsidies contribute largely to the economic viability of stockless organic systems, but their importance varies widely between the farms and production programs. The underlying heterogenous opportunity costs of conversion might motivate regionally and farm-type specific subsidy rates. Such differentiation avoids deadweight losses and can promote conversion where it is costly and currently lagging. Despite the high economic potential of organic farming found in our and other studies, conversion shares remain low, illustrating that other factors besides profitability are important for conversion decisions. The results thus indicate that policy incentives mainly based on subsidies may not be sufficient to motivate conversion and other differences in the production systems, such as in production and market risks, should be addressed by further specific policy instruments for organic farms.

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Chapter 5

Conclusion

5.1 Major contributions of the dissertation

In light of the EU's ambitions to achieve an ecological transformation of its agricultural sector, it is crucial to drive the adoption of ecological approaches by farms and increase the effectiveness of policies aimed at a more sustainable agriculture. First, this requires understanding of how sustainable performance can be driven by structural and policy factors to better target support for ecological approaches. Second, there is a need to understand how the attractiveness of ecological approaches to farmers as potential adopters can be increased to better align policy and societal goals with those of farmers (Latruffe et al. 2022). Given this need, the aim of this dissertation is to contribute to the body of knowledge on the sustainability of ecological approaches at farm level. It also identifies how policy and structural factors drive performance levels and gaps and may affect farmers' decisions to adopt these approaches.

The research activities carried out within the framework of this dissertation show that ecological approaches can increase the economic performance of farms and are therefore associated with a high economic potential. Three main drivers have emerged that largely contribute to the economic viability of ecological approaches. First, crop production can be associated with lower costs, largely due to lower direct costs and a reduced number of passes over the field with implications for machinery requirements. Second, the economic performance of ecological approaches is influenced by price premiums, which result from consumers' higher willingness to pay. These price premiums are particularly relevant for products produced according to organic standards. Third, public payments are found to considerably affect the economic performance, but their importance varies widely between ecological approaches. For example, an increase in legume production on dairy farms can be associated with a decrease in profits. The lack of price premiums implies a dependency on public payments for compensation. While relatively low levels of coupled support can lead to modest increases in legume shares, more substantial changes require considerable subsidies. Although price premiums are granted for organic products, public payments also contribute strongly to the economic viability of organic farming. However, their importance varies greatly between farms and production programs, reflecting underlying heterogeneous opportunity costs of conversion.

In this context, spatial structures have shown to strongly affect the economic performance of ecological approaches and the opportunity costs of their adoption. The effects of plot sizes and farm-plot distances on economic performance are found to be higher in conventional compared to organic farming systems, implying that potential profit gains from conversion to organic farming are higher for farms in more fragmented land markets. Thus, regional adoption rates of organic farming may be influenced by spatial structures, with plot sizes and farm-plot distances contributing to the spatial concentration of organic farms. Furthermore, the results of the dissertation show that the distance to an important trading partner, e.g., in the case of stockless organic production to an external biogas plant, can have a considerable impact on the economic performance. Long distances strongly reduce the economic potential of organic farming and may reduce the incentive to convert.

The study further highlights that the economic performance of ecological approaches depends largely on the regulatory constraints imposed by policy and private farming associations. The economic potential of stockless organic farming is highly dependent on import possibilities of nutrients as set under guidelines for organic farming. Nutrient flows from conventional agriculture, as here via biogas digestate, allow to overcome the lack of mobile on-farm N fertilizer and to thus enable to expand and intensify organic production. This contributes to rendering stockless conversion of specialized arable farming profitable under current market and policy conditions in Germany. Stricter restrictions on the import of off-farm N, as imposed by organic farming associations, further limit farmers' management options and shift crop rotation towards less profitable crops. Thus, while lower barriers for N imports, as set in the EU regulation on organic farming, can increase the economic potential of organic farming, stricter regulations are more in line with the traditional idea of organic farming and may increase credibility, thus maintaining price premiums in the long run.

In addition to public payments that subsidize specific ecological approaches, their adoption is also affected by policies that have other targets and are hence not explicitly intended to promote a particular approach. Regulation-specific restrictions on the application of N, such as those set by the Nitrates Directive, are found to affect the uptake of legume production. Less stringent regulations, such as allowing manure to be applied to legumes, can help to promote legume production on N-rich livestock farms. However, this can result in a trade-off where higher legume shares can be achieved at the expense of higher N leaching as manure application exceeds legume N requirements. Overall, there is a clear tendency for less stringent restrictions to increase the economic performance that might thus encourage the adoption of ecological approaches, with the risk of reducing their environmental benefits.

Changes in labor requirements associated with the adoption of ecological approaches are found to be heterogeneous, such that no clear tendency can be identified. In organic production, labor requirements are lower for most crops. However, the often-necessary shift to a more diversified crop rotation can also introduce more labor-intensive crops or increase their share. Higher labor requirements in livestock production and farm management in organic production can further increase the demand for labor. Given the heterogeneous effects on labor requirements and economic performance, the results on labor productivity are also mixed. This confirms that widely held beliefs about lower labor efficiency of ecological approaches are not necessarily valid.

In this dissertation, the adoption of ecological approaches is associated with a reduction in the use of inputs in crop production. First, the adoption of ecological approaches can be associated with a ban on certain inputs (e.g., mineral fertilizers and chemical pesticides in organic farming). Second, necessary changes in crop rotation can decrease the share of input-intensive crops in favor of crops that require fewer inputs. The reduction in input use can be associated with environmental benefits. On livestock farms, however, the environmental benefits can be dampened as large shares of the impact on certain environmental dimensions, such as global warming potential, can be attributed to the herd. In addition, the decline in input use can reduce the impact of price fluctuations. While N fertilizer prices strongly affect the profitability of conventional farming systems, the impact on organic farming profits is limited. In contrast, changes in the price of diesel reduce the profitability of conventional and organic farming systems on the case study farms to almost the same extent and thus have no impact on the economic potential of organic farming.

The methodological contributions of this dissertation include a structural analysis of a database on costs and resource requirements of field operations. The database contains information on field operations for more than one hundred crops, including, for example, a wide range of cereals, fodder and protein crops, as well as vegetables and catch crops, in both conventional and organic production. A regression model is applied to the database to derive the resource and labor requirements of field operations as a function of plot size and farm-plot distance. A total of 1.8 million regression functions covering eight positions (such as fuel and labor requirements, maintenance, and interest costs) are provided. They are used to derive for each crop labor and intermediate resource requirements that are associated with the use of machinery per hectare as a function of plot sizes and farm-plot distances. Thereby, various levels of mechanization as well as different types of tillage and cultivation are distinguished. These functions are a valuable tool for gaining further insight into the effects of plot sizes and farm-plot distances and provide a powerful database for comparative analyses of the production practices of different farming approaches, including, conventional and organic farming as well as, for example, non-tillage practices.

The regression functions are implemented in the bio-economic model FarmDyn, where they allow for a consideration of the effects of plot sizes and farm-plot distances. Combined with the introduction of additional economic (e.g. prices and direct costs) and agronomic (e.g., yields, crop rotational shares and fertilization requirements) data, the model is extended to cover the wide range of crops in detail. In doing so, the model allows differentiation between organic and conventional farming, as well as different tillage and cropping practices. This provides a powerful tool for detailed comparisons between conventional and organic farming practices and for assessing the differential impact of, for example, policy measures and technological change. In addition, the database allows for straightforward modification such that the data can be adapted to other circumstances or research questions. Thus, the dissertation contributes to a gap in the literature where the lack of adequate and detailed data is considered a major drawback for the analysis of ecological approaches. The extension of FarmDyn is used in the calculation of the economic potential of organic farming provided in Chapter 4.

As part of this dissertation, an N-balancing method is developed that reflects the specificities of conventional and organic production. It covers the above mentioned, more than one hundred crops in both farming systems. The method is based on simplified N fluxes and pools using parameterization from existing data and literature. This increases the applicability and adaptability of the method and allows the analysis of a large number of farms with a wide range of farm types. It is currently parameterized for German conditions but can be adapted to other conditions and extended to include additional crops without considerable effort. By implementing the method in the bio-economic model FarmDyn, it allows for improved analyses and comparison of organic and conventional farming systems, for example under changing nutrient regulations in policy impact assessment and analysis of the effects of management changes in arable systems. The new fertilization method helps to fill a gap in the literature, allowing organic farming to be captured in more detail and compared to conventional farming methods in existing bio-economic models.

5.2 Methodological discussion and research outlook

Bio-economic models, as applied in Chapters 2 and 4 of this dissertation are well suited for sustainability assessments of ecological approaches at farm-level and ex-ante identifications of policy impacts and structural factors on performance levels and gaps. They allow for a detailed representation of agricultural activities and their externalities by providing a comprehensive representation of biophysical processes and economic flows and their trade-offs (Janssen et al. 2010). Due to their ability to capture the heterogeneity of farms (Blanco 2016), they allow the identification of differential impacts of ecological approaches and their drivers. However, as supply-side models, BEFMs are characterized by price exogeneity, which prevents them from accounting for market feedback. This disregards the potential impact of policies and future developments on input and output prices, which determine the economic potential of ecological approaches. For example, the results of this dissertation suggest that higher profits in organic farming compared to conventional farming largely reflect price premiums. These, however, depend on the development of demand for organic products and may decrease in the future due to market saturation effects. Likewise changes in supply can have relevant market effects such as on prices and trade, with consequences for the environmental performance. This implies that the increase in organic production targeted by policy makers may lead to changes in crop choices towards, for example, more legumes and less sugarbeets and rapeseed. In addition, farms which have adopted ecological approaches are found to have lower land and labor productivity, which impacts overall food production (e.g., Lakner and Breustedt 2017; Niedermayr et al. 2022). While these changes are captured at farm level, the overall market feedbacks of changing quantities and prices are neglected including potentially higher import demand. In addition to market effects, policy feedback is not considered. The total budget for Voluntary Coupled Support for legumes, studied in Chapter 2, is capped at the national level to comply with World Trade Organization regulations. Increased production of legumes may lead to a greater drawdown of this budget and, thus, to a reduction in individual payments.

While BEFM are not capable of quantifying such feedbacks, (partial) equilibrium models (Britz et al. 2012) can provide insights into changes in trade flows, quantify market feedbacks resulting from shifts in production and demand, and estimate induced price changes. However, in comparison, farm-level analyses based on BEFMs provide greater modeling flexibility to capture the economic and environmental farm performance, as well as farm heterogeneity (Blanco 2016). In this context, the capability of using a sensitivity analysis can provide valuable insights into the effects of changes in uncertain parameters (Wossink and Renkema 1994). However, incorporating (partial) general equilibrium models into the analysis and establishing a feedback loop between both models would be a valuable extension of the analyses. This would allow for a more comprehensive understanding of the potential consequences of increased adoption on environmental performance and economic outcomes.

The studies carried out within this dissertation are based on (representative) case study analyses and provide valuable insights into the performance of ecological approaches at farm-level that are not yet covered in the literature. Different methods are used to analyze the changes in farm management and the associated effects on performance levels resulting from the adoption of ecological approaches in line with the aim of the respective study. In Chapter 2, the effects of two policies affecting legume production are endogenously modeled for two case study farms using FarmDyn. As the changes in farm management due to conversion to organic farming are more substantial, other methods instead of endogenous modeling are needed in Chapters 3 and 4. Chapter 3 analyzes case study farms that have recently converted to organic farming, providing high detail on production programs before and after conversion. However, the underlying selection bias renders it more likely to find a positive impact on profits than analyzing a sample of farms that remain in conventional production. In contrast, in Chapter 4, representative conventional case study farms are selected from a farm typology for the analysis in FarmDyn and converted to organic farming based on expert knowledge. It should, however, be noted that the adoption of ecological approaches, particularly the conversion to organic farming, is a farm-specific decision that depends on conditions both on- and off-farm (Sapbamrer and Thammachai 2021). Therefore, no generally applicable adoption process can be presented.

By choosing the northwest of Germany as a case study region, the dissertation studies adoption of ecological approaches in an intensive productive area where the political and societal goal of increasing sustainability in agricultural production remains particularly ambitious. Here, environmental conditions can be considerably improved (Früh-Müller et al. 2018), while favorable production possibilities drive opportunity costs of conversion. Despite the high opportunity costs, results of Chapters 3 and 4 indicate a high economic potential of organic farming. This suggests that the economic potential may be even higher in less intensive regions. The strength of the analyses lies in the large-scale sensitivity analyses delivering results beyond the current and regional specific economic contexts. This ensures that the studies provide meaningful findings that are relevant to a wide range of farms and render the results of interest beyond the case study regions and Germany. Clearly, a larger sample covering more heterogeneous farms from different regions is needed to generalize our findings and identify further drivers of performance and obstacles of conversion. Analysis at the level of a farm population is hampered as available databases do not cover ecological approaches well (Kerselaers et al. 2007; Latruffe et al. 2022). Observations before and after adoption with detail in farm management and structure are scarce in existing single farm records, such as the Farm Accountancy Data Network (FADN). Further, several environmental and social aspects as well as data on ecological farming approaches are currently not or only marginally covered by the FADN (Latruffe et al. 2022; Niedermayr et al. 2022). Extending research to larger samples hence requires either collection of primary data by dedicated studies or changes in statistical data coverage. The increasing availability of public datasets, as used in Chapter 3, might be a promising alternative.

Despite the high economic potential of organic farming described in Chapters 3 and 4, the share of conversion remains low both in the case study region and at higher level in Germany and the EU (Destatis 2021; Eurostat 2023). In this context, it should be considered that, first, higher profits for organic systems a largely due to price premiums. These are, however, dependent on access to organic value chains which is not always available. This is partly due to an insufficiently developed value chain, which lacks, for example, processing plants and storage options (DLG 2022; Piller 2023; Zukunftskommission Landwirtschaft 2021). For instance, German dairies have temporarily stopped purchasing from new suppliers, such that price premiums cannot be received after conversion (LWK NRW 2021).

Further, despite growing demand for organic products, the development is not sufficient to achieve the ambitious political targets for organic farming, which could mean that the price premium cannot be maintained (UBA 2023). Second, organic farmers face higher output prices and production risks related to quantity and quality as certain risk-reducing inputs are not allowed (e.g., Acs et al. 2009; Smith et al. 2019; Gardebroek et al. 2010; Serra et al. 2008). While risk-averse farmers are not willing to accept large variations in revenues across years (Acs et al. 2009), risk-loving farmers are more likely to convert in a shorter period of time (Kallas et al. 2010). In Chapter 2 and 4 FarmDyn is applied such that it reflects standard economic behavior by assuming a fully rational and profit-maximizing farmer. FarmDyn, however, incorporates stochastic programming, and is thus able to account for risk and uncertainty in agricultural decision-making. Expanding the study by applying this extension would be a valuable contribution to better understanding how farmers' attitudes toward risk affect the perceived performance of ecological approaches. Third, calculating the economic potential of organic production systems disregards that farms have to undergo an economically difficult 2-year conversion period, during which lower yields are sold at conventional prices (Acs et al. 2007). To draw conclusions about the economics of conversion, where investment decisions are critical, a dynamic rather than a comparative static approach is required. While FarmDyn generally supports fully dynamic simulations, the comparative static version of the model is used in this dissertation since it does not aim to predict conversion, but to identify drivers of performance and performance gaps.

Even though the decision to convert to organic farming is increasingly dependent on economic considerations (e.g. Flaten et al. 2006; Kleijn et al. 2019; Liu et al. 2018; Łuczka and Kalinowski 2020), it is also influenced by other factors. Among these factors are, for example, socio-demographic (e.g. gender, education), personal and social behavioral (e.g., norms and attitudes, interaction with other farmers and advisers) and supportive factors (e.g., access and familiarity with technologies) of farmers (e.g., Kleijn et al. 2019; Sapbamrer and Thammachai 2021; Thompson et al. 2023). This implies that farmers’ decisions to adopt organic farming do not depend on economic considerations alone, but are the result of an interaction of drivers to which profitability considerations contribute (Hansson et al. 2019). This in mind, the results of this dissertation should not be understood as prediction of farmers adoption behavior, but contribute to reveal barriers and opportunities for the adoption of ecological farming approaches. Incorporating a multi-criteria approach would be a valuable extension of the studies, as it enables the consideration of multiple objectives, beyond just profit, and would contribute to a more accurate representation of farmers’ behavior (Janssen and van Ittersum 2007).

A major methodological contribution of this dissertation is the development of an N-balancing method that allows for a more detailed representation of organic farming in existing bio-economic models, and its implementation in FarmDyn. The method is based on N-flows and pools of existing data and literature and characterized by a high degree of applicability and adaptability. This allows the analysis of a large number of farms with a wide range of farm types. Climate aspects such as temperature and precipitation, as well as the temporal availability of different N sources are currently only considered as regional average values in the implemented data. In addition, FarmDyn does not yet cover the soil carbon stocks and carbon-N relations, which strongly influence N availability, nor does it cover plant availability of different N compounds. The implemented parameters are therefore subject to uncertainties and natural variability, which can considerably affect the results of the analysis. The sensitivity analysis performed in Chapter 4 reveals this strong influence on the results for the economic potential. An extension of the modeling approach could address a better representation of the N available for plant growth and the different characteristics of N fertilizers and related externalities (Küstermann et al. 2010). Detailed and dynamic N fluxes can be provided by linking FarmDyn to specialized models, such as site-specific plant growth or biophysical models. In general, FarmDyn allows the linkage with other models, as demonstrated by Kuhn et al. (2020) who coupled a crop system model with FarmDyn to investigate the effects of the revised German Fertilization Ordinance. This is, however, associated with increased computing time and large data requirements, at the expense of easy adaptability to other conditions and the analysis of a large number of farms.

In its current form, the N-balancing method only allows the consideration of fixed yield levels. An extension with N-response curves would be valuable to allow for endogenous adjustments of yields with associated effects on fertilization and sustainable farm performance. At present, FarmDyn is capable of endogenously adjusting N-requirements based on cultivation intensities that affect yield levels. However, it should be noted that the available data is limited to a small number of crops under conventional production. Obtaining a comprehensive set of data to extend the N-response curves for a wide range of crops across various production systems included in the model is challenging due to the unavailability of sufficient data. Further, N-based yield projections are always subject to uncertainty, among others since the yield level is also influenced by other factors and nutrients. These are not yet covered by FarmDyn or, in the case of phosphate, only in a simplified way.

The analysis in Chapter 2 addresses the environmental effects of two policies at farm level. Due to the scale and methodology chosen, direct statements about effects on higher scale and environmental conditions cannot be made. First, assessing environmental effects on higher scale requires the consideration of market effects. For example, increased legume production reduces GWP of the case study farms mainly by lowering intermediate input requirements for mineral fertilizer and bought feeds. A simultaneous decrease in cereal production may lead to changes in the production program of other farms and in trade, which could offset on-farm reductions in GWP. Further, environmental effects are largely not farm-specific, but depend on the presence and interaction of multiple farms (Niedermayr et al. 2022). Hence, assessing N leaching at the level of an individual farm is not suitable for drawing conclusions about the impact on the quality of water bodies. This requires a simulation of N emissions over a larger area, for example, by including all farms at the watershed level of a water body. Second, developments in environmental indicators do not allow for direct conclusions about impacts on environmental conditions. While N leaching, for example, provides estimates of emissions from a farm, environmental objectives for water bodies target N concentrations. However, N concentrations of water bodies are strongly influenced by factors that are either not included in the analysis, such as the timing of fertilization, or that are not influenced by farm management, such as the rate of groundwater recharge.

Chapter 3 and 4 quantifies the labor use effects of organic farming. While labor requirements in livestock production and farm management increase with the conversion, results indicate that changes in labor requirements in crop production are heterogeneous such that no overall effect can be identified. It should, however, be noted that the studies do not distinguish by type of work. Thus, no conclusion can be drawn on whether organic farming requires different skills among participating farmers or is associated with higher labor diversity. Also, potential social effects (e.g., gendered effects), or effects on labor market cannot be evaluated. In this context, the incorporation of the detailed data base into FarmDyn, carried out as part of this dissertation, provides detailed insights into the field operations and machine applications required in crop production. Using these data, future studies can explore the employment effects of ecological approaches at farm level, providing information not only on quantity of labor use, but also on the type, quality, and diversity of labor required. By considering different levels of mechanization and the possibility to edit and expand the database, it is further possible, for example, to investigate the extent to which machines and technological progress can replace physical labor. This can be particularly interesting as the amount of labor required for some crops considerably increases under organic production, for example due to labor-intense weeding.

5.3 Policy implications

The aim of increasing sustainability in agricultural production has led to a shift in the political agenda. In the EU, for example, the CAP and the European Green Deal aim to accelerate the transition to a sustainable food system. In this context, various policies promote the introduction of ecological approaches aimed at reducing the negative environmental impact of agricultural production. One example of an ecological approach is the increased production and use of legumes. Various support measures targeting legume production have been implemented in the EU and Germany, including their contribution to a diverse crop rotation under the Common Agricultural Policy (LWK NRW 2023) and reducing competitive disadvantages of domestic protein crops through the Protein Crop Strategy implemented by the German government (BMEL 2023a). In addition, the EU offers the possibility of promoting legumes through Voluntary Coupled Support (VCS), which is currently not implemented in Germany (EC 2022). Results of Chapter 2 suggest that VCS can effectively promote legumes. However, achieving high shares of legumes requires a combination of other measures due to the high opportunity costs of production. In addition to policies directly promoting ecological approaches, such as legume production, another option is, thus, to lower their opportunity costs. One way to achieve this is by internalizing negative external effects production processes, for example trough a tax on N mineral fertilizers (e.g., Meyer-Aurich et al. 2020), to reduce their profitability while generating governmental revenue (WBAE and WBW 2016). However, there is ongoing debate on the benefits and drawbacks of economic measures addressing the negative external effects of N application, including taxes on N mineral fertilizers or N surpluses (e.g., Henseler et al. 2020; SRU 2015; WBAE and WBW 2016).

The study in Chapter 2 examines the effects and interaction of VCS for legumes and the national implementation of the Nitrates Directive, which is not specifically targeted at legume production. However, the study reveals that the design of the Nitrates Directive can considerably impact the level of legume production. This example illustrates the importance of considering policy coherence when implementing new policies to ensure that the desired objectives are achieved efficiently. As a prerequisite, different policy areas should be consulted and coordinated carefully. In addition to policy coherence, potential unintended effects of policies need to be considered. For example, increasing the competitiveness of legumes can result in their increased production as livestock feed. The greater availability of fodder legumes might enhance profitability of livestock production through lower feed costs, leading to a potential rise in demand for livestock farming, with associated negative environmental impacts, such as greenhouse gas emissions. On the other hand, legumes can contribute to greater sustainability in livestock production. This trade-off highlights the importance of detailed ex-ante analysis when implementing new policy measures, with farm-scale models being a helpful tool for such analysis.

Analyses for evidence-based policy must be based on sound and relevant data. In general, farm-scale models rely on detailed and ideally spatially explicit data from individual farms. In Germany, data protection standards impose restrictions on access to and analysis of such data (Pahmeyer et al. 2021), which limits the scope of farm-level analyses. Promoting the development of synthetic farm populations, such as for NRW by Pahmeyer et al. (2021), could be a way to provide the scientific community with farm-scale data without compromising data protection (Wimmer and Finger 2023). Further, information from existing European-scale databases does not provide sufficient farm-level data to accurately assess the sustainability of agricultural production (Kelly et al. 2018). An important step is therefore the transformation of the FADN into a Farm Sustainability Data Network (FSDN) database, which will extend the current mainly economic aspects to the environmental and social dimensions of farming (European Parliament and Council of the European Union 2023). This provides a valuable opportunity to improve the European Commission's monitoring and evaluation capacity for future sustainability challenges, for example by reporting on input quantities rather than expenditure, and by collecting data on farming practices not currently covered (e.g. tillage management, crop rotation, soil cover) (Latruffe et al. 2022). Policy makers should ensure research access to relevant and reliable data in order to promote meaningful research and enable evidence-based decision-making.

The research activities carried out as part of this dissertation show that ecological approaches can increase the economic performance of farms and can therefore be associated with high economic potential. Public payments contribute considerably to the economic viability of ecological approaches. Ecological approaches lacking price premiums, such as legume production, rely on public payments to maintain economic returns. However, as examined in Chapter 3 and 4, public payments also affect the economic performance of organic farming despite price premiums, rendering subsidies important for compensation. However, their importance varies widely across farms and production programs, reflecting underlying heterogeneous opportunity costs of conversion. This dissertation concludes that spatial structures, such as plot sizes and farm-plot distances as well as the distance to important trading partners, affect the economic potential of organic farming and determine the opportunity costs of adoption. They can thus contribute to the spatial concentration of organic farms, with regions characterized by lower production intensity and greater land fragmentation showing higher adoption rates than regions with intensive agriculture (Schmidtner et al. 2012). The literature discusses whether a spatially even distribution of organic farming or a concentration in certain locations is favorable (e.g. Taube et al. 2006). In areas with intensive production, conversion to organic farming can considerably improve the environment (Früh-Müller et al. 2018). This could motivate region- and farm-type-specific subsidy rates that reflect heterogeneous opportunity costs of conversion. Such differentiation avoids deadweight losses and can encourage conversion where it is costly and lagging. This would require policy to be designed in a more flexible manner allowing for targeted interventions (Latruffe et al. 2022; Moschitz et al. 2021; Niedermayr et al. 2022). Current policies do not, or only to a limited extent, reflect differences in opportunity costs. For example, the support for organic farming in Germany is differentiated according to the type of land use (e.g., arable or grassland) (MLV NRW 2023). A clear policy objective must be formulated as to whether an even distribution of organic farming is desired.

The findings in Chapters 2 and 4 of this dissertation demonstrate that the strictness of policy measures affects the economic potential of ecological approaches. Less stringent regulations can increase adoption rates and support the achievement of existing policy goals. However, relaxing regulations, such as those related to the application and import of N, may compromise the environmental benefits of ecological approaches. While lower barriers can promote adoption, stricter regulations can raise environmental standards (Seufert et al. 2017). In this context, relaxed regulations in organic agriculture can negatively affect customer perceptions and undermine its credibility (Blumenstein et al. 2014). This leads to increased criticism of organic farming (e.g., Deumlich et al. 2016) and can pose challenges in maintaining price premiums. In this context, the ambitious goals of the European Green Deal, e.g. in terms of area under organic farming (EC 2020), pose the risk of relaxing regulations in favour of high adoption rates. In order to maximize environmental benefits, it is crucial to find a balanced approach that ensures an adequate area under ecological approaches while maintaining strict environmental regulations. Stakeholders from policy and farming organizations should carefully consider these trade-offs when designing rules and regulations.

Despite the high economic performance identified in this dissertation and in the literature, adoption rates remain low (e.g., BMEL 2023b; EC 2023; Latruffe et al. 2022). This suggests that policy incentives mainly based on subsidies may not be sufficient to motivate conversion. In order to drive the adoption of ecological approaches at scale, policy makers need to consider other potential barriers to which profitability only contributes.

First, scientific evidence alone is not sufficient to increase the adoption of organic approaches. Farmers may lack access to information or question the transferability of scientifically proven benefits (Kleijn et al. 2019; Läpple 2010). To effectively promote ecological approaches, it is crucial to better engage farmers and stakeholders in the discourse and improve the dissemination of information. This requires a shift in agricultural education to include sustainability and ecological farming approaches (Zukunftskommission Landwirtschaft 2021). Policies should facilitate conventional farmers' access to ecological approaches and farmers, as interaction and peer learning play a considerable role in driving adoption (Sapbamrer and Thammachai 2021). In addition, extension services should cover a broader range of ecological approaches beyond organic farming, offering training in specific skills and techniques (Latruffe et al. 2022). Non-governmental producer organizations, such as organic farming associations or cooperatives, can complement the efforts of public agencies and contribute to the dissemination of information on ecological farming approaches and their economic performance (e.g., Barnes et al. 2021; Sapbamrer and Thammachai 2021).

Second, the results of Chapters 3 and 4 reveal that conversion to organic farming can be associated with an increase in labor requirements. Labor requirements in livestock production and farm management are found to be higher in organic farming systems. Similarly, labor demand in crop production can increase, particularly when crops requiring labor-intensive manual weed control measures are introduced into the crop rotation. This can be associated with labor peeks that require flexible adjustments in hiring labor, especially on farms lacking the necessary family labor force. By reducing the transaction costs of employment without compromising the working conditions of hired labor, policy can provide support to farmers (Latruffe et al. 2022). Nevertheless, labor and skill shortages are considered to be a major concern in the agricultural sector (Ryan 2023) and may thus hinder conversion. The results of Chapter 3 illustrate that the use of biogas digestate offers an economically viable option for making organic production independent of labor-intensive livestock production. In addition, technological progress and innovative techniques, such as the use of mechanical weeding robots, can considerably reduce labor requirements and be associated with high economic benefits (Shang et al. 2023; Sørensen et al. 2005). This may help to encourage the conversion of conventional farms for which high labor input is an obstacle. However, high investment requirements for the introduction of machinery and innovative techniques may prevent their adoption. This is particularly relevant as the adoption of ecological approaches can imply investments in new machinery, technology and buildings (Acs et al. 2007), as also illustrated by the case study farms in this dissertation. Accordingly, further research into innovative technologies and government incentives to support investments may be an important determinant of targeted support for ecological approaches.

Third, increasing the adoption of ecological approaches requires strengthening and expanding the relevant structures along the value chain. The presence of and distance to key trading partners, from input suppliers to various processors, distributors and retailers, can have a considerable impact on the economic performance of ecological approaches (Barnes et al. 2021), as illustrated by the findings in Chapter 4. Policies need to go beyond production incentives to include both upstream and downstream sectors that determine farmers' production and marketing opportunities (Barnes et al. 2021; Zukunftskommission Landwirtschaft 2021). In addition, price premiums have shown to have an important impact on the economic viability of organic farming (see Chapters 3 and 4). In order to considerably expand organic farming and increase the adoption of ecological approaches, it is essential to focus on changing consumer habits and increasing both their willingness to pay and their demand for products with environmental benefits (EC 2020; Latruffe et al. 2022). These efforts play a crucial role in creating marketing opportunities, sustaining price premiums, and introducing them for ecological approaches that currently rely on public payments (Barnes et al. 2021). The development and improvement of market-based instruments, including public (and private) certification schemes, could help to raise the visibility of environmental benefits and initiate a demand-driven transition (Latruffe et al. 2022; Niedermayr et al. 2022). Initiatives by private stakeholders are particularly valuable in the face of the limited policy options. For instance, regulations imposed by the World Trade Organization limit the implementation of policy measures that distort trade, including restricting on soybean imports in the context of imported deforestation (Pendrill et al. 2019). In addition to policy measures studied in Chapter 2, private stakeholders can instead promote the local production of legumes, for example by developing certified markets like GMO-free milk. This can be an interesting lever to establish price premiums and increase the profitability of locally grown legumes while contributing to reduce import quantities of soybeans. The success of such initiatives depends on supportive policies that promote the development of competitive value chains and support information campaigns or investments in new machinery which are, for example, required for legume processing (Meynard et al. 2018).

The design and diversity of policy measures play a crucial role in promoting the adoption and increasing the sustainability of ecological approaches. Their interaction with regulations of private initiatives and other policy measures and goals determines their effectiveness. This highlights the need to consider policies in a broader context rather than in isolation. The complexity makes it challenging to develop effective policies and requires the coordination between legislative processes, policy departments, and different stakeholders. In addition, increasing the adoption of ecological approaches depends not only on the production side, but also on the development of the entire value chain, including upstream and downstream sectors as well as consumer demand. Accordingly, encouraging an ecological transition requires a balanced use of a variety of policy instruments beyond the production side of agriculture. This underlines the importance of a holistic approach that replaces the currently prevailing agricultural policy with a food policy (Barnes et al. 2021), thus adding a more systemic perspective to the ongoing debate (Moschitz et al. 2021).

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Appendix of the dissertation

Appendix Chapter 2

Appendix 2.A Price data used in the sensitivity analysis

Table A2.1 Price ranges and average price used in the sensitivity analysis

		Germany			France		
Price	Good	Min	Mean	Max	Min	Mean	Max
Output	Winter wheat	117 €	165 € [(1)]	230 €	113 €	162 € [(3)]	216 €
Input	Soybean meal	333 €	429 € [(1)]	552 €	314 €	393 € [(4)]	497 €
Input	Concentrate 12% RP	155 €	193 € [(2)]	234 €	154 €	180 € [(5)]	211 €
Input	Concentrate 18% RP	184 €	229 € [(2)]	277 €	212 €	248 € [(5)]	290 €
Input	Concentrate 40% RP	311 €	387 € [(2)]	468 €	332 €	389 € [(5)]	455 €

Notes: [(1)] KTBL (2019); [(2)] DLR Westerwald Osteifel (2011); [(3)] French Ministry of Agriculture (2018); [(4)] IFIP (2017); [(5)] IDELE (2016). RP refers to the row protein content of the concentrates.

Appendix 2.B Correlation matrix

Table A2.2 Correlation between the prices of the goods, as considered in the Latin Hypercube sampling

	Soybean meal	Concentrates
Winter wheat	0.65	0.8
Soybean meal		0.9
Concentrates		0.95

Notes: Price correlations of winter wheat, soybean meal and the three concentrates are the same for Germany and France. Source: Own calculation based on Eurostat (2019).

Appendix 2.C References

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Appendix Chapter 3

Appendix 3.A Exemplary presentation of required field operations and related resource requirements and costs in conventional and organic winter wheat production as reported by *Kuratorium für Technik und Bauwesen in der Landwirtschaft*

Table A3.1 Simplified presentation of required field operations and related resource requirements and costs in conventional winter wheat production (bread wheat)

Frequency (count year^{-1})	Time period (half of a month)	Field operation	Labor requirements (h ha^{-1})	Fuel requirements (l ha^{-1})	Machine costs (€ ha^{-1})
0.2	Sep 1	**Soil sampling** pickup truck	0.03	0.03	0.72
1	Sep 1	**Spread mineral fertilizer** mounted manure spreader	0.11	1.08	2.67
1	Sep 2	**Ploughing** reversible 10-furrow plough	1.02	27.16	58.49
1	Oct 1	**Harrow** seedbed combination	0.45	6.9	30.51
1	Oct 2	**Transport of seeds**	0.23	1.23	5.37
1	Oct 2	**Sawing** seed drill	0.48	5.38	22.21
1	Oct 2	**Visual weed monitoring** pickup truck	0.16	0.27	1.38
1	Oct 2	**Water transport** for plant protection measures, tank trailer	0.23	1.15	3.92
1	Oct 2	**Plant protection measures** pesticide sprayer	0.2	1.48	7.64
1	Feb 1	**Nitrogen monitoring** pickup truck	0.14	0.14	3.90
1	Feb 2	**Visual monitoring** pickup truck	0.13	0.12	0.77
1	Feb 2	**Mineral fertilization** mounted manure spreader	0.09	1.03	2.12
1	Mar 2	**Visual monitoring** pickup truck	0.13	0.12	0.77
1	Apr 1	**Mineral fertilization** mounted manure spreader	0.1	1.05	2.24
1	Apr 1	**Water transport** for plant protection measures, tank trailer	0.23	1.15	3.92
1	Apr 1	**Plant protection measures** pesticide sprayer	0.2	1.48	7.64
1	Apr 2	**Water transport** for plant protection measures, tank trailer	0.23	1.15	3.92
1	Apr 2	**Plant protection measures** pesticide sprayer	0.2	1.48	7.64
1	May 1	**Visual monitoring** pickup truck	0.13	0.12	0.77
1	Jun 1	**Mineral fertilization** mounted manure spreader	0.09	1.02	1.95
1	Jun 1	**Water transport** for plant protection measures, tank trailer	0.23	1.15	3.92
1	Jun 1	**Plant protection measures** pesticide sprayer	0.2	1.48	7.64
1	Aug 1	**Harvesting** combine harvester	1.55	26.94	154.28
1	Aug 1	**Transport of harvest** transport trailer	0.23	1.72	11.8

1	Aug 1	**Storing and drying**	0.61	0	108.48
0.33	Aug 2	**Liming** mounted manure spreader	0.07	1.01	3.78
1	Aug 2	**Stubble working, shallow**	0.45	6.84	24.05
1	Sep 2	**Stubble working, deep**	0.48	7.82	24.79

Notes: The data is extracted from KTBL (2019b). Resource requirements and costs are reported for 2 km farm-plot distance, 2 ha plot size and a mechanization level of 200 kW. Ploughing is selected as tillage method and a medium soil and yield level is specified. Machine costs include costs of depreciation, interests, maintenance, lubricants and additional costs (e.g., insurance fees and taxes).

Table A3.2 Simplified presentation of required field operations and related resource requirements and costs in organic winter wheat production (feed wheat)

Frequency (count year^{-1})	Time period (half of a month)	Field operation	Labor requirements (h ha^{-1})	Fuel requirements (l ha^{-1})	Machine costs (€ ha^{-1})
0.2	Sep 1	**Soil sampling** pickup truck	0.03	0.03	0.76
1	Oct 2	**Ploughing** reversible 10-furrow plough	1.02	26.53	57.68
1	Oct 2	**Harrow** seedbed combination	0.45	6.9	27.34
1	Oct 2	**Transport of seeds**	0.21	1.16	4.7
1	Oct 2	**Sawing** seed drill	0.48	5.38	21.85
1	Oct 2	**Mechanical weed control** harrows	0.17	2.37	10.67
1	Feb 1	**Nitrogen monitoring** pickup truck	0.14	0.14	4.155
1	Feb 2	**Visual monitoring** pickup truck	0.12	0.12	0.85
1	Mar 1	**Mechanical weed control** harrows	0.17	2.37	10.67
1	Mar 1	**Organic fertilization** Liquid manure, drip hose booms	0.46	7.58	30.77
1	Aug 1	**Harvesting** combine harvester	1.55	21.71	148.71
1	Aug 1	**Transport of harvest** transport trailer	0.23	1.71	8.26
1	Aug 1	**Storing and drying**	0.31	0	54.25
0.33	Aug 2	**Liming** mounted manure spreader	0.07	0.98	3.68
1	Aug 2	**Stubble working. shallow**	0.45	6.84	23.51
1	Sep 2	**Stubble working, deep**	0.48	7.82	24.21

Notes: The data is extracted from (KTBL 2019b). Resource requirements and costs are reported for 2 km farm-plot distance, 2 ha plot size and a mechanization level of 200 kW. Ploughing is selected as tillage method and a medium soil and yield level is specified. Machine costs include costs of depreciation, interests, maintenance, lubricants and additional costs (e.g., insurance fees and taxes).

Appendix 3.B Model selection and regression performance

Five different regression models were tested on the 1.8 million regression functions from which the best was chosen based on the distribution of the Akaike information criteria (AIC). Due to the large number of regression functions and the resulting required computing time and memory load, automatic model selection was not feasible. As seen from the table below, regression model 3 performed best by returning the lowest AIC for 44% of the 1.8

million regression functions. It also performed best with regard to the median adjusted R-squared and the median coefficient of variation of the root mean squared deviation (CVRMSD).

Table A3.3 Model selection metrics for the five considered regression models

Regression Model	% of regressions for which model returns the lowest AIC	Goodness-of-fit: Median Adj. R^2	Goodness-of-fit: Median CVRMSD
$\hat{Y}_{FOC_{SM}} = \beta_0 + \beta_1 P + \beta_2 D$	0.03%	58.19%	6.28%
$\hat{Y}_{FOC_{SM}} = \beta_0 + \beta_1 P + \beta_2 P^2 + \beta_3 D + \beta_4 D^2 + \beta_5 PD$	3.63%	76.52%	4.73%
$\hat{Y}_{FOC_{SM}} = \beta_0 + \beta_1 P + \beta_2 P^2 + \beta_3 \sqrt{P} + \beta_4 D + \beta_5 D^2 + \beta_6 PD$	44.21%	96.70%	1.88%
$\hat{Y}_{FOC_{SM}} = \beta_0 + \beta_1 P + \beta_2 P^2 + \beta_3 \sqrt{P} + \beta_4 D + \beta_5 D^2$	27.71%	96.57%	1.91%
$\hat{Y}_{FOC_{SM}} = \beta_0 + \beta_1 P + \beta_2 P^2 + \beta_3 \sqrt{P} + \beta_4 D$	24.83%	96.40%	1.95%

Table A3.4 below provides additional detail for the selected regression model 3. It reports the distribution of the CVRMSD for each dependent variable and for all 1.8 million regression functions. Table A3.5 summarizes the distribution of the adjusted R-squared.

Table A3.4 Coefficient of variation of the root mean squared error (CVRMSD) separated by the dependent variable and for the overall model. Presented are the median and mean values as well as the first and third quantiles

Dependent variable	CVRMSD: Median	CVRMSD: Mean	CVRMSD: Quantile (25%,75%)
Labor requirements	0.041	0.091	0.023, 0.064
Fuel requirements	0.018	0.077	0.011, 0.030
Depreciation cost	0.014	0.057	0.007, 0.027
Interest costs	0.016	0.058	0.009, 0.029
Maintenance costs	0.020	0.067	0.013, 0.032
Costs for lubricants and electricity	0.017	0.076	0.010, 0.030
Other costs (e.g. insurance, taxes)	0.022	0.059	0.011, 0.036
Area output	0.014	0.018	0.010, 0.018
Overall model	0.019	0.065	0.011, 0.035

Table A3.5 Distribution of the adjusted R-squared over all regression functions

Parameters	Median
Min	0.063
0.01%	0.471
0.1%	0.700
1%	0.706
10%	0.921
20%	0.942
30%	0.948

40%	0.952
Mean	0.954
Median	0.967
60%	0.977
70%	0.990
80%	0.998
90%	1.000
Max	1.000

Appendix 3.C Costs in conventional and organic crop production as reported by *Kuratorium für Technik und Bauwesen in der Landwirtschaft* at the example of crops produced by the case study farms

Crop production costs (per hectare) and their composition are presented below for the crops produced by the case study farms, covering expenditures on intermediate inputs and costs related to machinery use for the required field operations. Intermediate inputs include seeds, fertilizers and pesticides and are taken from KTBL (2019a). These data are independent of plot sizes, farm field distances and mechanization levels. Expenses for fertilizers consider lime and mineral fertilizer while manure is assumed to be available free of charge. In organic production, costs of fertilizers refer to lime only. Costs for pesticides consider expenditure on herbicides, fungicides, insecticides and growth regulators. Costs arising from machine applications (e.g. tillage, manure and fertilizer spreading, plant protection measures) consider labor, fuel and machine costs. The data is extracted from KTBL (2019b), considering average plot sizes of 2 ha, farm-plot distances of 2 km and a mechanization level of 200 kW, based on ploughing as the tillage method. Machine costs include costs for depreciation, interests, maintenance, lubricants and additional costs (e.g. insurance fees and taxes). Labor costs reflect assumed wage costs of 20 € per hour (IG Bauen-Agrar-Umwelt et al. 2019). For some crops typically found in organic production only no data are available for conventional production.

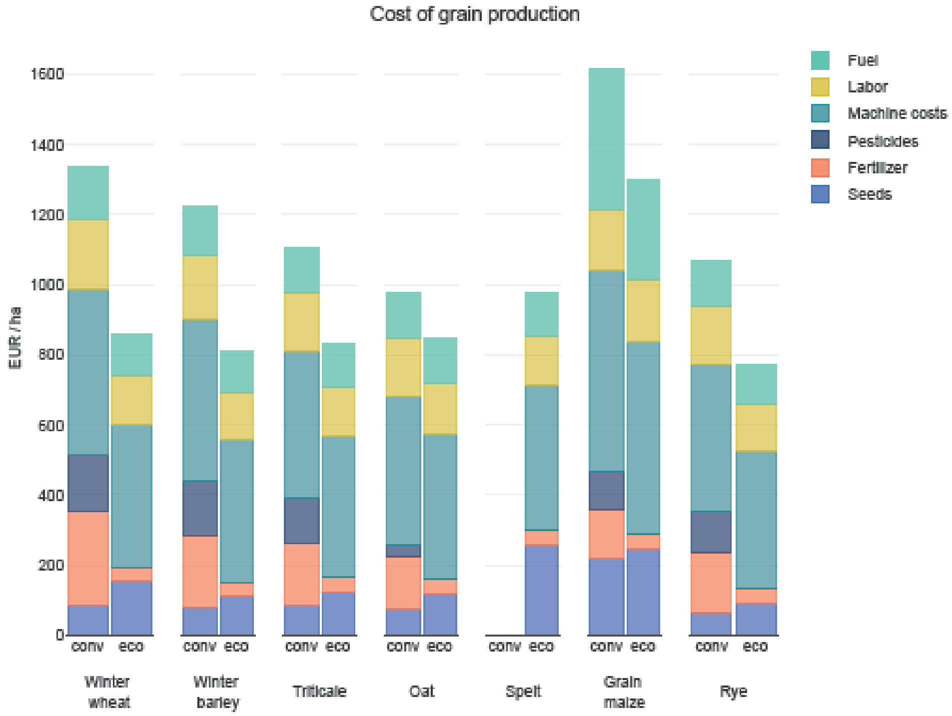

Figure A3.1 Costs of grain production under conventional and organic production

Notes: Expenditures on seeds, fertilizer and pesticides are extracted from KTBL (2019a). Fuel, labor and machine costs are taken from KTBL (2019b), assuming plot sizes of 2 ha, farm-field distances of 2km and a mechanization level of 200 kW. For spelt no data are available for conventional production.

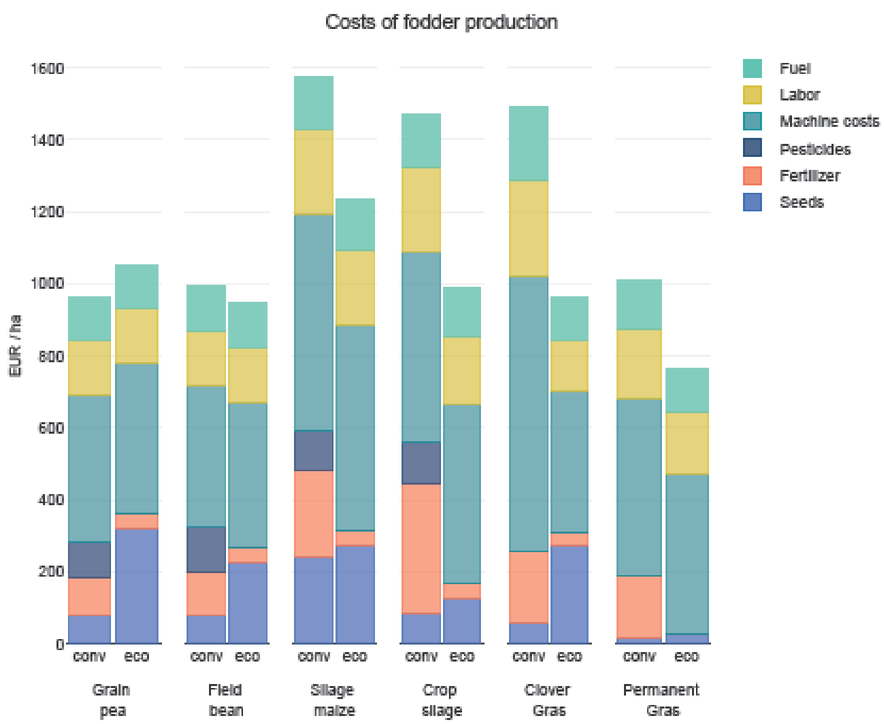

Figure A3.2 Costs of fodder production under conventional and organic production

Notes: Expenditures on seeds, fertilizer and pesticides are extracted from KTBL (2019a). Fuel, labor and machine costs are taken from KTBL (2019b), assuming plot sizes of 2 ha, farm-field distances of 2km and a mechanization level of 200 kW.

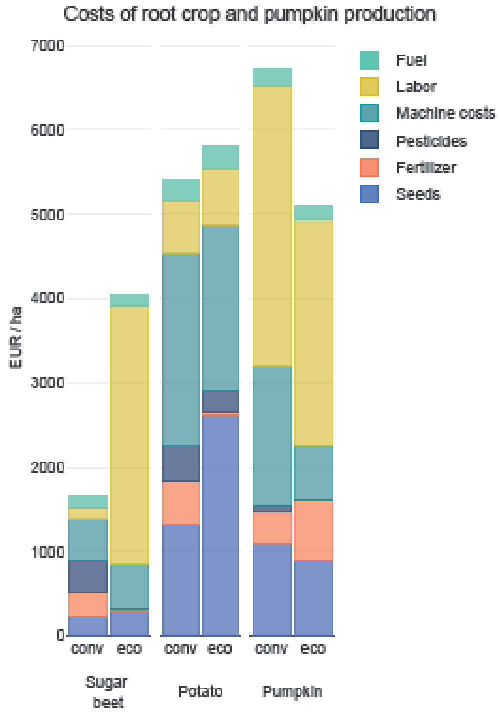

Figure A3.3 Costs of root crop and pumpkin production under conventional and organic production.

Notes: Expenditures on seeds, fertilizer and pesticides are extracted from KTBL (2019a). Fuel, labor and machine costs are taken from KTBL (2019b), assuming plot sizes of 2 ha, farm-field distances of 2km and a mechanization level of 200 kW.

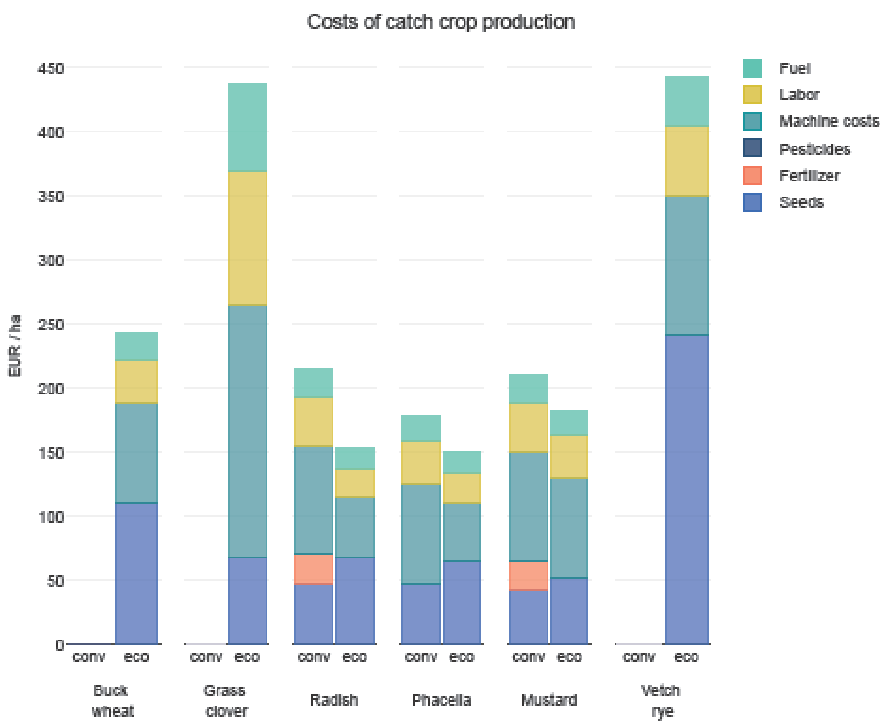

Figure A3.4 Costs of catch crop production under conventional and organic production

Notes: Expenditures on seeds, fertilizer and pesticides are extracted from KTBL (2019a). Fuel, labor and machine costs are taken from KTBL (2019b), assuming plot sizes of 2 ha, farm-field *distances of 2km and a mechanization level of 200 kW. For vetch rye and buck wheat no data are available for conventional production.*

Appendix 3.D References

IG Bauen-Agrar-Umwelt; Landesverband Schleswig-Holstein e.V.; Landesverbände Nordrhein-Westfalen e.V. und Hessen e.V.; Landesgruppen Niedersachsen und Rheinland-Pfalz/Saarland im Bundesverband Lohnunternehmen e.V. (2019): Lohn- und Gehaltstarifvertrag vom 24. April 2019 für die Arbeitnehmerinnen und Arbeitnehmer der Land- und Forstwirtschaftlichen Lohnunternehmen in Schleswig-Holstein, Niedersachsen, Nordrhein-Westfalen, Rheinland-Pfalz, Saarland und Hessen. Kassel, Germany. https://www.landwirtschaftskammer.de/bildung/pdf/fa-lohntarifvertrag.pdf, (accessed: 3/4/2020).

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Appendix Chapter 4

Appendix 4.A Multi-stage structural survey to generate crop rotations

The farm typology by Kuhn and Schäfer (2018) provides information on average crop shares for the three case study farms: '*specialist cereals, oilseeds, protein crops*' (COP) in SCR 143, '*cereals, oilseeds, protein crops and root crops combined*' (COP+R) in SCR 141 and '*various field crops combined*' (COM) in SCR 142. Thereby, regional differences between soil-climate regions are considered. Given the low share of organic arable farms, these shares are assumed to represent the conventional production system. Based on the information, a conventional and an organic crop rotation are developed for each case-study farm. The crop rotations are the result of a structured survey of a panel of agricultural consultants specialized in conversion of arable farms in NRW (Figure A4.1). Within a multi-stage survey process the experts were encouraged to propose crop rotations and revise and comment on crop rotations of the other participants while their anonymity was ensured. The feedback and updated crop rotations were presented to and revised by all experts until crop rotations were agreed upon by all experts.

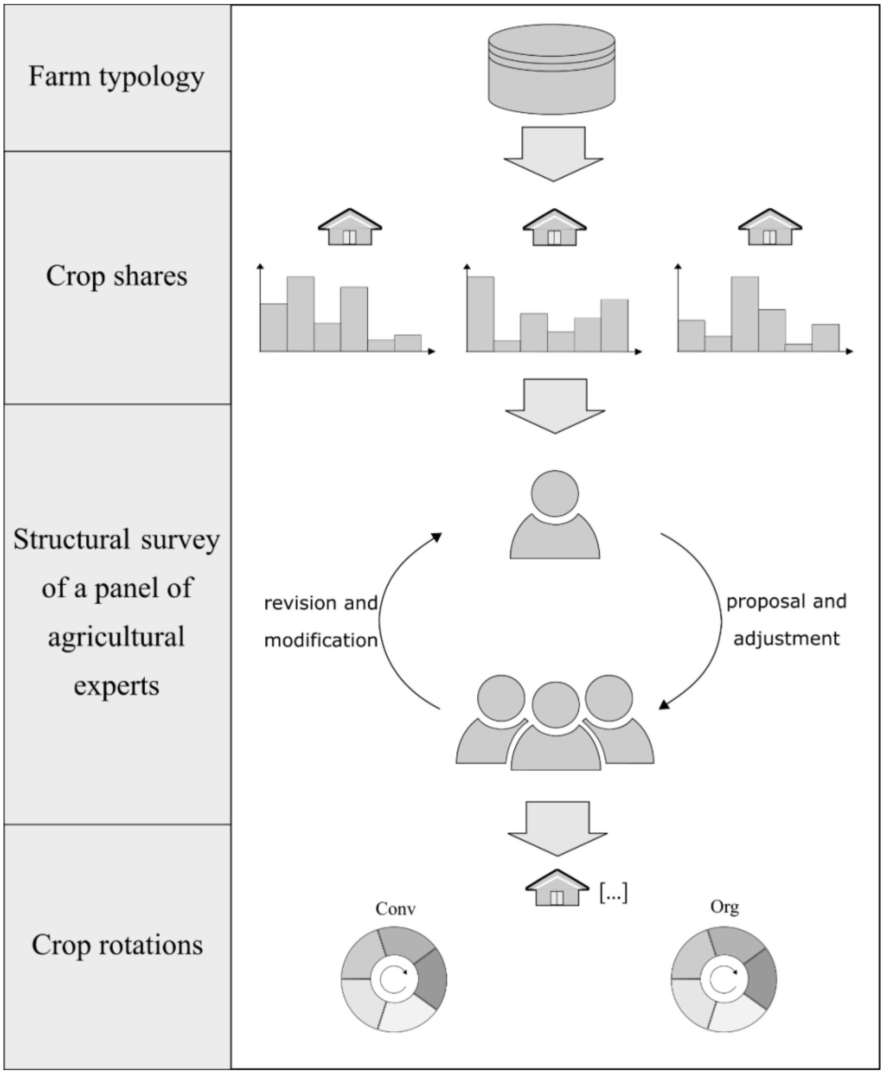

Figure A4.1 Structure of the multi-stage structural survey to generate the conventional (conv) and organic (org) crop rotations for each case study farm

Appendix 4.B Model parameterization

Table A4.1 Employed prices and yields under conventional and organic farming

	Prices (€ t^{-1})		Yield (t ha^{-1})					
			Farm COP		Farm COP+R		Farm COM	
	Conv	Org	Conv	Org	Conv	Org	Conv	Org
Winter wheat	176	390	8.4	-	8.8	4.5	8.1	4.2
Winter barley	161	320	7.4	-	8.4	4.8	7.3	-
Winter triticale	162	-	7.7	-	-	-	-	-
Spelt	-	484	-	3.0	-	3.4	-	-
Summer barley	-	440	-	3.8	-	-	-	3.6
Summer wheat	-	337	-	4.3	-	-	-	-
Oat	-	320	-	-	-	4.5	-	4.4
Grain maize	175	361	9.3	-	10.0	6.0	9.3	5.5
Potato	189	450	-	-	53.0	35	48.2	30.0
Sugar beet	35	-	-	-	82.0	-	77.2	-
Winter rapeseed	379	900	3.6	1.9	3.6	-	-	-
Field beans	-	400	-	3.5	-	3.9	-	-
Soybeans	-	630	-	-	-	-	-	2.3
Clover grass	-	-	-	42.0	-	50.0	-	42.0

Notes: Data on yields in conventional (Conv) and organic (Org) farming systems are based on 5-year average of NRW (Land-Data 2021), complemented by values for Germany when missing (KTBL 2019b). Yield levels are adjusted to each farm to account for regional differences of each soil-climate region (JKI 2019; Pahmeyer 2021). Data on prices are based on averages values for the period 2011-2020 (AMI 2021) and complemented as required by KTBL (2019b). Both price and yield data were reviewed by the expert panel and adjusted where deemed necessary. The acronyms correspond to Farm COP: Specialist cereals, oilseeds, protein crops; Farm COP+R: Cereals, oilseeds, protein crops and root crops combined; Farm COM: Various field crops combined.

Table A4.2 Prices for fertilizers

	Prices	N content
Urea Ammonium Nitrate (%N)	210 € dt^{-1}	28%
Ammonsulfatsalpeter (%N)	260 € dt^{-1}	26%
Biogas digestate	6,6 € $m^{3\ -1}$	5,5kg $m^{3\ -1}$

Notes: Data on prices and N content of mineral N-fertilizers and biogas digestate (Achilles et al. 2020; Bruns 2022)

Table A4.3 Average plot sizes and farm-plot distances

	Farm COP	Farm COP+R	Farm COM
Plot size (ha)	3.0	3.3	2.9
Farm-plot distance (km)	3.4	3.6	4.3

Notes: Average plot sizes and farm-plot distances specified for each farm type and soil-climate region (Pahmeyer et al. 2021). The acronyms correspond to Farm COP: Specialist cereals, oilseeds, protein crops; Farm COP+R: Cereals, oilseeds, protein crops and root crops combined; Farm COM: Various field crops combined.

Appendix 4.C N fertilization scheme for bio-economic farm-scale models

As part of the study, a Nitrogen (N) fertilization scheme for farm models in line with the specifics of organic farming practices is developed and implemented in FarmDyn. Commonly applied methods and data are based on conventional farming systems which are, among others, characterized by high yield levels and nutrient contents in harvested crops and crop residues (Stein-Bachinger et al. 2004). In organic farming systems, N flows differ considerably from those in conventional systems (Pandey et al. 2018). For example, due to the pre-dominant use of mineral N-fertilizers or manure in conventional agriculture, crop shares of legumes, especially of fodder legumes, are rather low and N stemming from legumes is not, or in a simplified way considered in nutrient accounting (Stein-Bachinger et al. 2004). N is a scarce production factor and legumes represent an important source of N especially in stockless farms (Küstermann et al. 2010; Stein-Bachinger et al. 2004). At the same time, N is the most important yield-generating factor and its efficient use determines to a high degree the success of the farm (Weckesser et al. 2021).

So far, only few methods for nutrient balancing are available that consider the specific conditions of organic farming (e.g. Korsaeth and Eltun 2000; Küstermann et al. 2010; Pandey et al. 2018; van der Burgt et al. 2006). These N management systems aim to (1) provide a better understanding of the N dynamics and N cycles, (2) assess the agroecosystem performance, for example by estimating N losses and changes in N stocks, or (3) provide support in the decision-making process (Weckesser et al. 2021). Because of their divergent objectives, these existing methods do not consider all N sources and sinks that are relevant to determine the fertilization requirements of crops in bio-economic models (Weckesser et al. 2021). Therefore, a N balancing method suitable for the application in bio-economic farm models is developed in the context of the presented work. This method includes all relevant N flows and allows the calculation of fertilization requirements (1) at the level of a single plot, (2) for a variety of crops (3) under both conventional and organic production.

Table A4.4 Nitrogen (N) sources and sinks included in the N fertilization scheme

Source	Acronym	Unit	References
N requirements			
of harvested main and by-products	*Nharvest*	kg N ha^{-1}	
of non-harvested crop residues	*Nresidues*		
N content in main product, by-product, and residues	*NcontM* *NcontR*	kg N t^{-1}	Bachinger et al. 2015; BMEL 2017; Köhler and Kolbe 2007
Crop yield	*Y*	t ha^{-1}	JKI 2019; KTBL 2019b; Land-Data 2021; Pahmeyer 2021
Ratio main and by-products	*α*	%	Bachinger et al. 2015; Köhler and Kolbe 2007
Share of by-product sold	*β*	%	
Quantity of crop residues	*r*	t ha^{-1}	Bachinger et al. 2015
N inputs			
Symbiotic N fixation	*Nfixation*	kg N ha^{-1}	Küstermann et al. 2010; Stein-Bachinger et al. 2004
N content of legumes	*Nneed*	kg N ha^{-1}	Bachinger et al. 2015; BMEL 2017; Köhler and Kolbe 2007
Ndfa (N derived from atmosphere)	*Ndfa*	%	Anglade et al. 2015; Li et al. 2015
Share of legumes	*L*	%	KTBL 2019b
N mineralization from crop residues	*NminResidues*	kg N ha^{-1}	
N in residues	*Nresidues*	kg N ha^{-1}	
Share of N available to subsequent crop	*γ*	%	Stieber 2021
N added by crop seed	*Nseeds*	kg N ha^{-1}	
N content in seeds	*NcontSeed*	kg N kg^{-1}	Kolbe and Köhler 2008
Applied quantity	*q*	kg ha^{-1}	KTBL 2019b
Soil mineral N content, spring	*Nmin*	kg N ha^{-1}	LWK NRW 2021
N mineralization, vegetation period	*NminVeg*	kg N ha^{-1}	LTZ 2021
Non-symbiotic N fixation	*NasymFix*	kg N ha^{-1}	Stein-Bachinger et al. 2004
Atmospheric N deposition	*Ndeposition*	kg N ha^{-1}	Gauger 2013
Total mineral N fertilization	*NminFert*	kg N ha^{-1}	
Total N in biogas digestates	*Nferment*	kg N ha^{-1}	
N outputs			
Application losses of synthetic fertilizer and biogas digestates	*NminFertLoss NfermentLoss*	kg N ha^{-1}	Haenel et al. 2018; IPCC 2006; Stehfest and Bouwman 2006
N leaching	*Nleach*	kg N ha^{-1}	Richner et al. 2014
Denitrification N loss	*Ndenitrification*	kg N ha^{-1}	Hermsmeyer and van der Ploeg 1996; Stein-Bachinger et al. 2004
N loss at plant senescence	*Nsen*	%	Sainju 2017

Notes: Data used to calculate Nitrogen (N) requirements of crops as well as N sources and sinks considered to calculate N fertilization requirements, including details on references accessed.

All flows are calculated as total N (kg N ha^{-1}) if not stated otherwise.

$$Nneed_c \leq Nfix_c + NfixSelf_{leg} + NminResidues_c + Nseed_c + Nmin_c + NminVeg_c + NasymFix_c + Ndeposition_c + Nferment_c - NfermentLoss_c + NminFert_c - NminFertLoss_c - Nleach_c - Ndenitrification_c - Nsen_c \quad (1)$$

N requirements are specified in detail for each crop c and not for the overall crop rotation. The N requirements of a crop $Nneed$ are calculated based at the level of a whole plant, considering N in harvested main and by-products $Nharvest$ and crop residues $Nresidues$, including non-harvested by-products, stubbles and roots. Detailed data on N concentration in the main product $NcontM$ and by-product and residues $NcontR$ are available for organic (Bachinger et al. 2015; Köhler and Kolbe 2007) and conventional production (BMEL 2017). Considering the crop yield Y [t ha^{-1}] and information on the ratio between main and by-products α [%], the share of by-product sold β [%] as well as the quantity of crop residues r [t ha^{-1}], total N requirements are estimated:

$$Nneed_c = Nharvest_c + Nresidues_c \quad (2)$$

$$Nharvest_c = \frac{1}{1000} * Y_c * (NcontM_c + \alpha_c * \beta_c * NcontR_c) \quad (3)$$

$$Nresiudes_c = \frac{1}{1000} * (Y_c * \alpha_c * NcontR_c * (1 - \beta_c) + NcontR_c * r_c) \quad (4)$$

The N requirements of a crop are met considering different N sources and sinks. Values calculated both endogenously in FarmDyn and exogenously are used for this purpose, based on data from various sources, such as scientific papers, governmental agencies, official statistics and planning handbooks (Table A4.4).

First, N mineralization of crop residues $NresiCarryOver$ are estimated using method provided by Stieber (2021):

$$NresiCarryOver_c = Nresidues_c * \gamma_{cn,l,s} \quad (5)$$

Thereby, the share γ [%] of N in residues $Nresidues$ available to subsequent crop is affected by the carbon-to-nitrogen ratio of the biomass cn, the length of the vegetation period of the subsequent crop l as well as the soil type s. As FarmDyn is used in a comparative-static mode without considering multiple plots, it is not known which crop follows after a specific crop. Therefore, a pool of N $NresiPool$ [kg N] is implemented at farm scale

(Heinrichs et al. 2021). The pool summarizes the calculated per hectare $NresiCarryOver$ multiplied with the area X [ha] of each crop:

$$NresiPool = \sum_{c} X_c * NresiCarryOver_c \tag{6}$$

This total N-pool $NresiPool$ is distributed to the different crop areas X. To avoid implausible distributions to individual crops, on each hectare the uptake of N from mineralized residues $NminResidues$ cannot exceed the maximum per hectare mineralization $NresiCarryOver$ any crop:

$$\sum_{c} X_c * NminResidues_c = NresiPool \tag{7}$$

$$with \quad NminResidues_c < \max_{c} NresiCarryOver_c \tag{8}$$

Symbiotic N fixation $Nfixation$ of a legume leg is estimated applying a method of Stein-Bachinger et al. (2004), by accounting for the total N content of legumes $Nneed$, the share of N derived from atmosphere $Ndfa$ [%] and the share of legumes L [%] in biomass of legume-nonlegume mixtures:

$$Nfixation_{leg} = Nneed_{leg} * Ndfa_{leg} * L_{leg} \tag{9}$$

N fixation of legumes is highly dependent on several factors. $Ndfa$ values vary widely in literature (Anglade et al. 2015), as a result of, for example, different measurement methods, different soil and weather conditions and fertilization practices. In the underlying study, data from Anglade et al. (2015) are applied, reporting median values of a literature review on the most important legumes in Europe. For legume catch crops, $Ndfa$ are taken from Li et al. (2015). The share of legumes in legume-nonlegume mixtures is extracted from KTBL (2019a).

$Nfixation$ reduces the requirements of a legume for N that is not fixed by the legume itself and can further provide N to the subsequent crop. Thereby, the share of $Nfixation$ included in the harvested legume $NfixSelf$ is removed from field and thus, not available for the crop rotation. The share of symbiotic N fixation available to the crop rotation $NlegCarryOver$ is thus defined as:

$$NlegCarryOver_{leg} = Nfixation_{leg} - NfixSelf_{leg} \tag{10}$$

$$with \quad NfixSelf_{leg} = Nharvest_{leg} * Ndfa_{leg} * L_{leg} \tag{11}$$

Following the method to distribute N from mineralized crop residues to the crop rotation, a pool of N $NlegPool$ [kg N] is integrated at farm-scale, summarizing the per hectare $NlegCarryOver$. $NlegPool$ is distributed to the crop areas X, whereby the uptake of N from legume fixation $Nleg$ per hectare cannot exceed the maximum per hectare $NlegCarryOver$ of any legume.

The input of N through seeds $Nseed$ is estimated by considering the N content $NcontSeed$ (Kolbe and Köhler 2008) and the applied quantity q of seeds (KTBL 2019a). Nutrient supply from N mineralization in spring $Nmin$ are based on the 5-year average of annual samplings for each crop in the case study region, considering crop-specific rooting depths (LWK NRW 2021). $NminVeg$ accounts for N delivery from soil available to crops during vegetation period and after Nmin-sampling for different crops and soil types (LTZ 2021). Non-symbiotic N fixation $NasymFix$ is reported to be rather low. As no comprehensive data of site-specific amounts are available, it is set to 5 kg N ha^{-1} as indicated by Stein-Bachinger et al. (2004). Atmospheric immissions in form of wet and dry deposition $Ndeposition$ are estimated at 10 to 40 kg ha^{-1} in Germany (Stein-Bachinger et al. 2004). In the case study region NRW, which is characterized by high stocking densities and industrial areas, N deposition is rather high (Stein-Bachinger et al. 2004) and set to 27.4 kg N ha^{-1} (Gauger et al. 2008). Due to rainfed production, only, N inputs from irrigation water are not considered (Sainju 2017).

The N requirements of crops can additionally be covered by fertilization. FarmDyn depicts fertilization activities with a monthly resolution to reflect environmental and economic impacts. As livestock manure is considered unavailable on the stockless farms, substrates stemming from the fermentation of biomass in biogas plants provide the only mobile, N-rich fertilizer $Nferment$ in organic farming systems. Under conventional production, N requirements can further be covered by the application of mineral N fertilizer $NminFert$. Unavoidable losses that occur during the application of synthetic N fertilizer $NminFertLoss$ and biogas digestates $NfermentLoss$ are considered (IPCC 2006; Haenel et al. 2018; Stehfest and Bouwman 2006). For biogas digestates, further N losses arising during application are considered, respecting details of the month and technique of application (Haenel et al. 2018). It is assumed that biogas digestates are applied directly after delivery such that no storage losses occur on the case study farm.

Further losses from fertilizer application occur when they are applied at low crop demand (Sainju 2017). These N losses from leaching $Nleach$ are estimated based on the SALCO-NO3 method by Richner et al. (2014) and depend on soil and climatic condition, crop types and month of application. Denitrification losses $Ndenitrification$ from soil are influenced by numerous factors and no consistent values exist (Stein-Bachinger et al, 2004). In Germany, Stein-Bachinger et al. (2004) suggest denitrification losses between 10 and 20 kg N ha^{-1} while Hermsmeyer and van der Ploeg (1996) report losses in agricultural soils in the case study region of between 15 and 35 kg N ha^{-1}. Thus, we consider denitrification losses with 20 kg N ha^{-1}. N losses through plant senescence $Nsen$ are set to 5% of aboveground plant N (Sainju 2017). N losses through soil erosion and surface runoff and gas emissions are reported to be small (Sainju 2017) and are not considered.

Appendix 4.D Calibration bounds

Table A4.5 Calibration bounds applied for each farm and farming system

	Farm COP		Farm COP+R		Farm COM	
	Conventional	Organic	Conventional	Organic	Conventional	Organic
Yields (%)	8	8	6	6	4	5
Output prices (%)	8	8	6	5	5	5
Production costs (%)	5	5	5	5	4	5
Input prices (%)	5	5	5	5	3	5
Labor coefficients (%)	0	5	5	5	0	5
Objective						
Lower bound (%)	94	90	97	95	96	96
Upper bound (%)	96	92	98	96	98	97

Notes: Maximal allowed relative deviations (down- or upward) from original, crop specific parameter value. The bounds for the objective refer to the optimal profit before calibration. The acronyms correspond to Farm COP: Specialist cereals, oilseeds, protein crops; Farm COP+R: Cereals, oilseeds, protein crops and root crops combined; Farm COM: Various field crops combined.

Appendix 4.E Parameter selection for sensitivity analysis

Distance to biogas plant

The density of biogas plants spatially varies within NRW. While there is a high density in the north and west of NRW, the region where intensive livestock production dominates, it is considerably lower in the southeast. Nevertheless, there are several biogas plants in almost every district (Karbach-Nölke 2017). To account for different distances to biogas plants, determining the costs of delivering biomass to the biogas plant and transporting the ferment from it to the farm, a sensitivity analysis is performed that considers distances between 0.5 and 50 km.

Organic subsidies

Subsidies granted for organic farming are an important source of income for organic farms (Jaime et al. 2016). Subsidies for maintaining organic arable farming vary between the federal states of Germany and range from 189 to 273 € ha^{-1} (BLE 2022). The level of subsidies for the new funding period in 2023 has not yet been determined. In this study, the impact of different levels of subsidies is assessed by varying the level of support between 0 and 500 € ha^{-1}.

Prices and yields of organic products

Prices and yields of organic products have a strong impact on economic potential. Annual fluctuations as well as an uncertain development with increasing share of organic farming represent a risk for farmers. This study therefore covers fluctuations in prices and yields beyond currently observed levels (-50 to +50% of converted prices and yields) (AMI 2021; Land-Data 2021).

Input prices for fertilizer and diesel

Prices for agricultural inputs are subject to strong fluctuations and have partially risen sharply in recent past. In particular, fertilizers and soil improvers as well as energy and lubricants have contributed to the increased input costs (DEFRA 2022; World Bank 2022). To account for future price uncertainties, this study covers a wider range of prices for mineral N fertilizers and diesel, including prices not yet observed (0.5 – 3 € l^{-1} diesel; 50 - 500% of the implemented price of the respective fertilizer) (Achilles et al. 2020; Statista 2022; World Bank 2022).

Soil mineral N content

The amount of mineral N available in the soil in spring, *Nmin*, is an important source of N. However, *Nmin* values are subject to large annual and spatial fluctuations and depend, among others, on weather, cultivation methods and soil properties (LWK NRW 2022). In particular when access to flexible N fertilizers is limited, this can impact estimated fertilizer requirements and the economic performance of crop rotation patterns. The analysis accounts for these uncertainties by using minimum and maximum values of reported values of the last 10 years for each crop for NRW (2013-2022) as a range for the sensitivity analysis (LWK NRW 2021).

Appendix 4.F Results of the sensitivity analysis

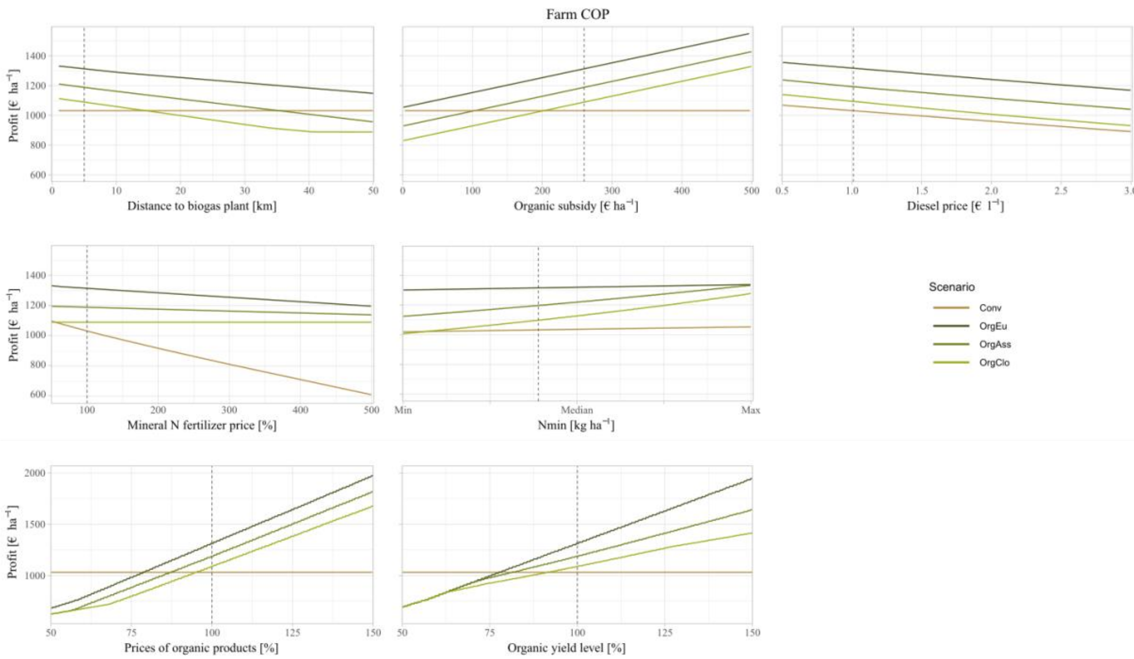

Figure A4.2 Results of the sensitivity analysis of farm COP

Notes: The acronyms correspond to Farm COP: Specialist cereals, oilseeds, protein crops; Conv: Conventional production; OrgEU: Organic production according to EU regulation; OrgAss: Organic production according to regulation of private farming association; OrgClo: Organic production with closed nitrogen-cycle. Nmin: Soil mineral N content in spring. The dashed lines show the parameter values implemented in the baseline. The implemented mean values of Nmin varies for each crop. Here, the dashed line represents the mean value as average over all crops in the conventional and organic crop rotation. The y-axis scales differ as specified.

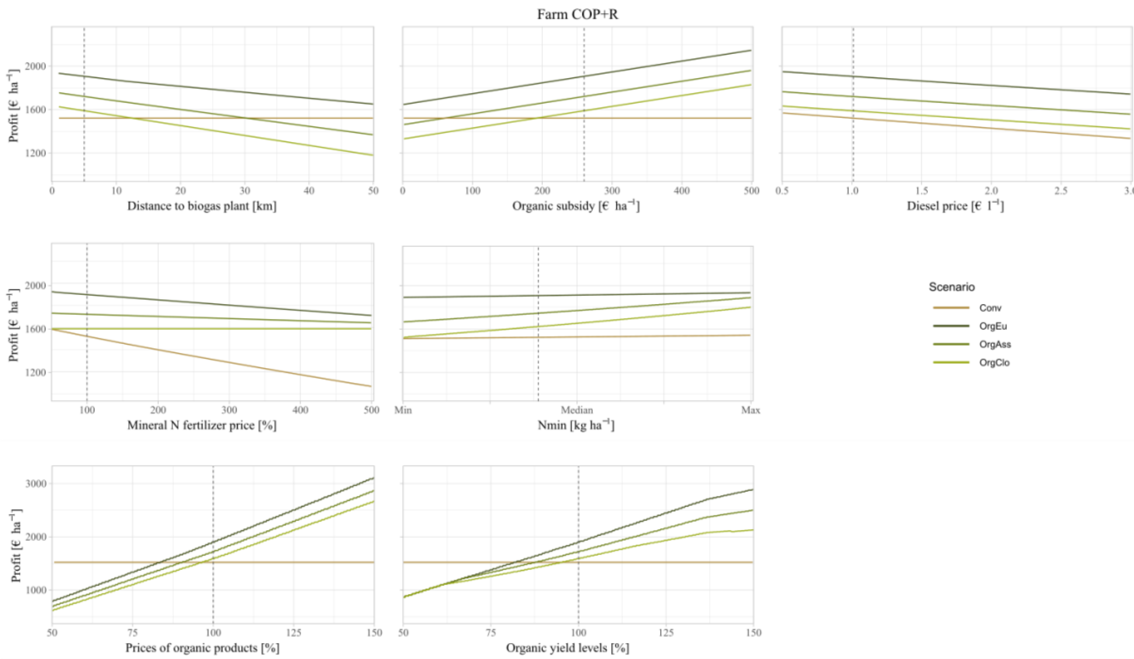

Figure A4.3 Results of the sensitivity analysis of farm COP+R

Notes: The acronyms correspond to farm COP+R: Cereals, oilseeds, protein crops and root crops combined; Conv: Conventional production; OrgEU: Organic production according to EU regulation; OrgAss: Organic production according to regulation of private farming association; OrgClo: Organic production with closed nitrogen-cycle. Nmin: Soil mineral N content in spring. The dashed lines show the parameter values implemented in the baseline. The implemented mean values of Nmin varies for each crop. Here, the dashed line represents the mean value as average over all crops in the conventional and organic crop rotation. The y-axis scales differ as specified.

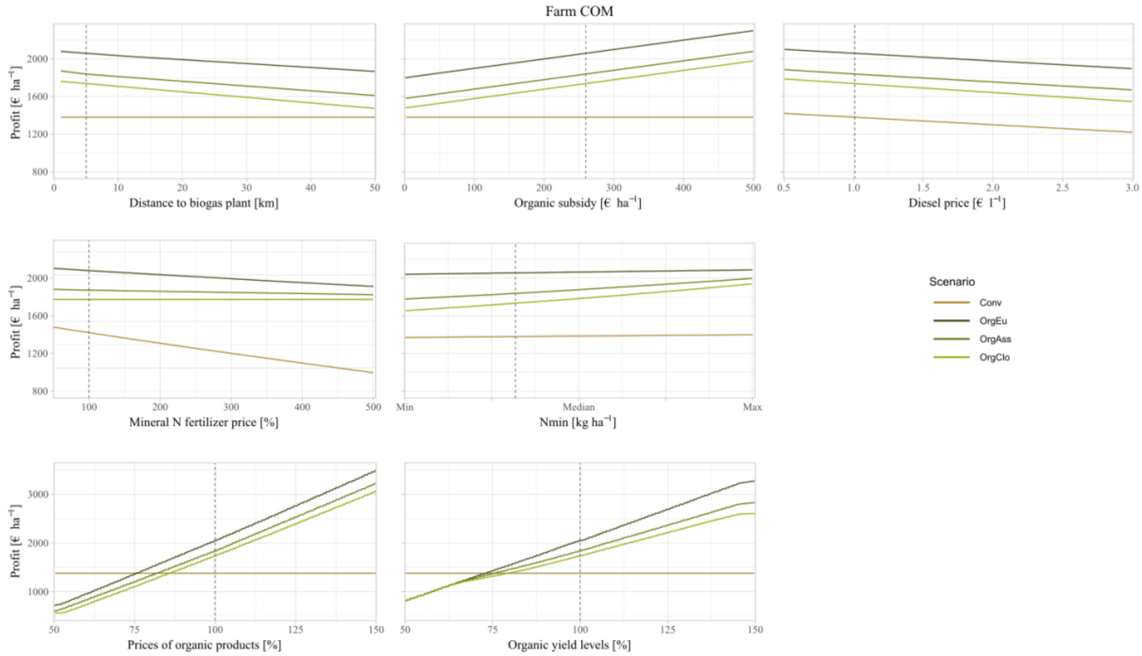

Figure A4.4 Results of the sensitivity analysis of farm COM

Notes: Acronyms correspond to Farm COM: Various field crops combined; Conv: Conventional production; OrgEU: Organic production according to EU regulation; OrgAss: Organic production according to regulation of private farming association; OrgClo: Organic production with closed nitrogen-cycle. Nmin: Soil mineral N content in spring. The dashed lines show the parameter values implemented in the baseline. The implemented mean values of Nmin varies for each crop. Here, the dashed line represents the mean value as average over all crops in the conventional and organic crop rotation. The y-axis scales differ as specified.

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