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Sustainable intensification: Farmers' adoption behaviour and environmental outcomes

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Summary

Sustainable intensification measures imply implementing changes in farming systems to improve environmental outcomes without compromising economic outputs. In order to assess the achievement of these outcomes, the dissertation at hand investigates the role of farmers' decision-making with respect to the effective implementation of sustainable intensification measures. The dissertation consists of three empirical studies, each dealing with one aspect of the decision process.

The first study focuses on sustainable intensification measures as the *decision objects*. A systematic literature review of 349 scientific publications builds the basis to develop a conceptual model of sustainable intensification, where four fields of action structure the portfolio of sustainable intensification measures. This conceptual model allows particularising local priority measures and regional measure portfolios in focus group discussions with stakeholders. The second study analyses farmers' *decision rationales* for these regional portfolios. An explorative approach based on multivariate probit and path modelling links farmers' positive experience with their sustainable intensification measures used to their intentions to broaden the portfolios with additional measures. Several complementary relationships in the use of sustainable intensification measures are established. The second and third study rest on farm survey data from the northern German Plain collected in 2017. The third study links adoption behaviour and *decision outcomes* by analysing eco-efficiency gains achieved by using agronomic sustainable intensification measures based on a theoretical model. Eco-efficiency is measured as the distance of current farm production to the production possibility frontier in the direction of the environmental outcome. Adopters show higher average eco-efficiency scores than a control group of matched non-adopters and determine a meta-frontier. However, most adopters do not fully exploit the ecological improvement potential of their farm.

This dissertation shows the capacities of sustainable intensification measures for on-farm environmental improvement. The capacity for improvement depends on farmers' decisions on how effectively they apply sustainable intensification measures. Political intervention schemes and future research to support effective implementation and full exploitation of improvement potentials are discussed.

Zusammenfassung

Nachhaltige Intensivierungsmaßnahmen beinhalten Änderungen in landwirtschaftlichen Systemen, um Umweltergebnisse zu verbessern ohne wirtschaftliche Ergebnisse zu beeinträchtigen. Um die Erreichung dieser Ergebnisse zu beurteilen, untersucht die vorliegende Dissertation die Entscheidungsfindung von Landwirten bezüglich der wirksamen Implementierung nachhaltiger Intensivierungsmaßnahmen. Die Dissertation besteht aus drei empirischen Studien, die sich jeweils mit einem Aspekt des Entscheidungsprozesses befassen.

Die erste Studie konzentriert sich auf nachhaltige Intensivierungsmaßnahmen als *Entscheidungsgegenstand*. Ein systematischer Literaturreview von 349 wissenschaftlichen Publikationen bildet die Grundlage für die Entwicklung eines konzeptionellen Modells der nachhaltigen Intensivierung, in dem vier Handlungsfelder das Portfolio nachhaltiger Intensivierungsmaßnahmen strukturieren. Das konzeptionelle Modell ermöglicht die Spezifizierung lokaler Schwerpunktmaßnahmen und regionaler Maßnahmenportfolios in Fokusgruppendiskussionen mit Stakeholdern. Die zweite Studie analysiert *Entscheidungsgründe* der Landwirte für regionale Portfolios. Ein explorativer Ansatz basierend auf multivariater Probit- und Pfadmodellierung verknüpft positive Erfahrungen der Landwirte mit bereits genutzten nachhaltigen Intensivierungsmaßnahmen und ihre Absichten, das Portfolio um zusätzliche Maßnahmen zu erweitern. Mehrere komplementäre Beziehungen bei der Anwendung nachhaltiger Intensivierungsmaßnahmen werden festgestellt. Die zweite und dritte Studie basieren auf betrieblichen Umfragedaten aus der norddeutschen Tiefebene von 2017. Die dritte Studie verbindet Nutzungsverhalten und *Entscheidungsergebnisse* durch die Analyse von Ökoeffizienzgewinnen, die durch den Einsatz agronomischer nachhaltiger Intensivierungsmaßnahmen erzielt werden, basierend auf einem theoretischen Modell. Ökoeffizienz wird durch die Distanz der aktuellen landwirtschaftlichen Produktion von der Produktionsmöglichkeitsgrenze in Richtung des Umweltergebnisses gemessen. Nutzer haben im Durchschnitt höhere Ökoeffizienzwerte als eine Kontrollgruppe vergleichbarer Nicht-Nutzer und bestimmen eine Meta-Grenze. Die meisten Nutzer schöpfen jedoch das ökologische Verbesserungspotenzial ihres Betriebs nicht vollständig aus.

Die Dissertation zeigt die Kapazitäten nachhaltiger Intensivierungsmaßnahmen für die Verbesserung der Umweltergebnisse des Betriebs. Die Verbesserungskapazitäten hängen von den Entscheidungen der Landwirte darüber ab, wie effektiv sie nachhaltige Intensivierungsmaßnahmen nutzen. Politische Interventionen und zukünftige Forschung zur Unterstützung einer effektiven Umsetzung und vollständigen Ausnutzung der Verbesserungspotenziale werden diskutiert.

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List of Abbreviations

AES	Agri-environmental scheme
CAP	Common Agricultural Policy
DDF	Directional distance function
DEA	Data envelopment analysis
EU	European Union
FADN	Farm Accountancy Data Network
FAO	Food and Agriculture Organization of the United Nations
FoA	Field of action
H2020 ERA-Net	Horizon 2020 European Research Area Networks
IACS	Integrated Administration and Control System
MEA	Millennium Ecosystem Assessment
MTR	Meta-technology ratio
MVP	Multivariate probit model
PLS	Partial least square
PPS	Production possibility set
RAA	Reasoned Action Approach
RISE	Rural Investment Support for Europe Foundation
RQ	Research question
SI	Sustainable intensification
TEEB	The Economics of Ecosystems and Biodiversity
UAA	Used agricultural area
UN	United Nations

Sustainable intensification:
Farmers‘ adoption behaviour and environmental outcomes

1 Introduction

1.1 Problem statement

Societal motivation to move away from current ways of food production is apparent in actions and behaviour: Researchers have been setting up interdisciplinary alliances to integrate knowledge on agricultural production and environmental conservation strategies (Foley *et al.*, 2011). Policymakers, for instance in the European Union, frame economic, environmental and social goals as prerequisite for agricultural support policies (European Commission, 2017). Consumers' demand regarding environmentally-friendly produced food for which farmers are fairly remunerated has been steadily increasing (Feldmann and Hamm, 2015).

The current state of agriculture renders the necessity to strengthen efforts. Globally, the agricultural sector, especially in highly-intensified production systems, contributes to pass planetary boundaries (Foley *et al.*, 2011; Conijn *et al.*, 2018). The safe operating space for the world's biophysical sub-systems has already been surpassed with regard to biodiversity loss, climate change and the nitrogen cycle (cf. Rockström *et al.*, 2009). The increase in global food demand driven by the growing world population (UN, 2015) and welfare-induced changes in dietary habits (Thornton, 2010) puts pressure on production systems. Likewise, agricultural productivity shows high regional variation (Fuglie *et al.*, 2012). Other sectors, such as bioenergy production, compete for scarce resources such as land, water or nutrients (Cordell *et al.*, 2009; Popp *et al.*, 2014).

The concept of *sustainable intensification (SI)* of agriculture targets solutions for sustainable agricultural production focused on the role of producers. SI follows the idea that food provision and farm income goals and environmental protection objectives are not necessarily contradictory. The core definition states that SI increases or at least stabilizes yields on existing agricultural areas while simultaneously reducing environmental harm or increasing the flow of environmental services (Pretty *et al.*, 2011). In the words of Gunton *et al.* (2016), 'Sustainable intensification means changes to a farming system that will maintain or enhance specified kinds of agricultural provisioning while enhancing or maintaining the delivery of a specified range of other ecosystem services measured over a specified area and specified time frame.' Proponents argue that many of these changes, i.e. SI measures and practices, exist to contribute to economic, ecological and social sustainability goals (Pretty and Bharucha, 2014). Resource-saving inter and mixed cropping, precision farming technologies, landscape planning to connect habitats, and regional value chains represent some illustrative examples at the farm and landscape scales.

Several studies have examined the goal attainment of SI: SI production systems have been shown to generate environmental benefits in field trials (e.g., Townsend *et al.*, 2016). Local knowledge is successfully applied for regionally adjusted food production according to best-practice examples (Bebbington, 1997; Buckwell *et al.*, 2014). SI improvement potentials have been extrapolated to national and global scales. Simulation results find that SI systems may reduce yield gaps (Mueller *et al.*, 2012) and exploit unused spatial potentials (Scherer *et al.*, 2018). Still, adoption rates of SI measures are partially low and vary across measures (Dicks *et al.*, 2019). Farms do not always realize improvements (Firbank *et al.*, 2013).

To evaluate the success or failure of SI, farmers' perspectives on implementing SI measures and shifting production to an SI-based system cannot be neglected. Farmers' decision-making is a core aspect to study implementation of conservation practices in economics and social psychology (cf. Yoder *et al.*, 2019). Their knowledge of existing alternatives, motivation and capabilities to adapt as well as their belief in the usefulness of changes are essential factors that may determine whether or not new production approaches are adopted and widespread (Dessart *et al.*, 2019). Likewise, subsequent to adopting the effectiveness of how SI measures are used by farmers and which outcomes are generated depend on these behavioural aspects.

With this dissertation, we[1] aim at analysing farmers' contributions to sustainable food production systems through sustainable intensification. We target a clear picture on the capacities for environmental improvement. The decision process that needs to be taken into account to follow this objective consists of three components: the SI measures potentially available for adoption and implementation (***decision objects***), farmers' ways of making the adoption decisions (***decision rationales***), and the results they achieve by adopting SI measures (***decision outcomes***).

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[1] The plural 'we' is used throughout this dissertation as major parts are based on research jointly conducted with co-authors, namely chapters 2, 3 and 4. The introductory (Chapter 1) and final discussion (Chapter 5) are written in sole authorship but reflect the results of the other chapters.

1.1.1 Decision objects

Farmers may choose from a set of available SI measures constituting the objects of decision-making. Two aspects are central for a definition of SI measures. The first is the openness of the concept in terms of the practical implementation. Approaches, practices or technologies are not excluded as long as they serve the purpose of creating environmental and economic benefits (Franks, 2014). SI embraces measures of conservation agriculture as well as genetically modified organisms (Wezel *et al.*, 2015). Small-scale optimisations of land use, such as precision farming (e.g., Kidd, 2012), belong to SI as well as regional land-sparing or sharing (e.g., Phalan *et al.*, 2011b). Management optimisation on the farm level, for instance, through the use of production residues (e.g., Homann-Kee Tui *et al.*, 2015), and resource and knowledge sharing in regional networks (e.g., Pretty *et al.*, 2011) denote examples for SI research. The openness regarding practical implementation has been raised as a major point of critique on the SI concept (e.g., McDonagh, 2014). The second aspect to define SI measures is their variation across regional contexts (Garnett *et al.*, 2013). At the end of the 1990's the concept originally emerged targeted at providing sustainable yield increases in developing countries (Pretty, 1997b). The European policy debate on SI is centred around local approaches for agricultural systems (Buckwell *et al.*, 2014). The sub-national level, for instance the regional or landscape scale, is the appropriate unit of analysis concerning farmers' adoption behaviour and SI outcomes (Barnes, 2016).

According to Pretty (2018) SI rather emphasizes outcomes than means. The lacking practical foundation of the concept poses a key problem for studying adoption and potential benefits of SI measures (Barnes, 2016). Unlike studies on the adoption of policy programmes or technological innovations, the object of adoption is not easy to grasp. The theoretical foundation that would help to bridge the gap between the generic and practical definition of SI is weak (cf. Petersen and Snapp, 2015) and results in calls for a coherent SI definition (e.g., Gunton *et al.*, 2016). Some approaches exist to compile SI measures for specific contexts (e.g., Dicks *et al.*, 2019 for the UK). However, to go beyond case study evidence, structured evidence on SI measures and a process to subsequently particularise the general knowledge for specific regional contexts are needed.

1.1.2 Decision rationales

The motives and rationales of farmers to adopt SI measures are a comparably marginal aspect in studies on SI although farmers' knowledge in defining local SI measures is a key aspect in the original framing (Pretty, 1997a). Farmers' willingness to adopt SI measures is not directly considered within the SI concept (Barnes, 2016). Studies on the implementation of SI measures mostly stem from developing countries and refer to case study evidence (Pretty, 1997a; Pretty and Bharucha, 2014). Few structured econometric analyses on determinants of the decisions to adopt, such as features of the farm holding or farmers' socio-economic and behavioural characteristics, directly refer to the SI concept (e.g., Shiferaw and Holden, 1998; Kassie *et al.*, 2015a; Läpple *et al.*, 2017).

In the literature on farmers' adoption behaviour, numerous examples address farmers' adoption behaviour of voluntary conservation measures (cf. Yoder *et al.*, 2019), agri-environmental schemes (cf. Dessart *et al.*, 2019) or new technologies (cf. Sunding and Zilberman, 2000). Thus there is overview on the determinants that may shape SI decision rationales (e.g., Knowler and Bradshaw, 2007; Wauters and Mathijs, 2014). Furthermore, adoption decisions may differ according to the characteristics of the decision objects in terms of the observability of outcomes or whether new practices can be tested in small-scale trials (cf. Reimer *et al.*, 2012). Existing evidence may serve as guidance to derive and test hypotheses on relevant decision determinants for SI.

SI measures often show benefits in smart mixes (Pretty and Bharucha, 2014). Therefore, farmers need to decide between different sets of measures. Kassie *et al.* (2015a) take this aspect of joint decision-making into account for a narrow set of agronomic SI measures and find interdependencies among the single adoption decisions. The portfolio of SI measures may be even broader (cf. Section 1.1.1.). The outcomes of optimising a portfolio of potentially interrelated SI measures are challenging to predict for farmers as they may affect cost ratios, labour requirements and administrative business structures (Barnes and Thomson, 2014). Thus farmers face a situation of complex decision-making, which has been criticised of being not sufficiently acknowledged when evaluating adoption behaviour (cf. Pathak *et al.*, 2019 for precision agriculutre). Studying the SI adoption behaviour from a portfolio perspective contributes to shed light on interrelations among decisions on SI measures as an aspect of the decision process.

1.1.3 Decision outcomes

As outcomes, SI may achieve gains in all aspects of sustainability, including the economic, ecologic, social or even the ethical domain (Barnes and Poole, 2012). Measuring and defining sustainability has resulted in a widespread field of research starting with the Brundtland (1987) report and touching multiple disciplines. Likewise, differing regional priorities need to be acknowledged for the evaluation of sustainability outcomes (Godfray and Garnett, 2014). For the context of an African small-holder system with an unexploited yield potential, Kassie *et al.* (2015b) investigate the impact of SI measures on average yields as well as yield stability. In developed countries, with already highly intensified production systems, SI focuses on conservation and environmental protection without compromising yields (Barnes, 2016). Measurement of these environmental outcomes mostly requires the use of indicators and proxies when on-farm measurement is not possible. Mahon *et al.* (2018) for instance define 110 potential indicators for SI based on interviews with stakeholders. Using efficiency approaches allows considering multiple outcomes simultaneously, such as economic and environmental farm outcomes, and enhances the indicator method by determining the potential of farmers to improve compared to a frontier of efficient outcome combinations (e.g., Gadanakis *et al.*, 2015; Areal *et al.*, 2018). However, studies using outcome indicators or efficiency approaches mainly monitor indicator development and differences between farms but do not trace back results to the adoption of specific SI measures (e.g., Firbank *et al.*, 2013; Barnes and Thomson, 2014; Firbank *et al.*, 2018).

There is a long tradition in the economic literature of programme evaluation to study causal effects of interventions to acknowledge that decision makers select whether to adopt or not (cf. Blundell and Costa Dias, 2009). Thus the observed effects when comparing outcomes of SI adopters and non-adopters can be biased when these two groups differ systematically. The difference in outcomes cannot be associated to measure implementation without controlling for self-selection. Besides the study of Kassie *et al.* (2015b), this problem has not been acknowledged in studies on SI outcomes and has not been related to studying of environmental achievements of SI measures.

1.1.4 Research questions

The reviewed scientific discourse for evaluating sustainable intensification shows gaps in adequately taking the perspective and role of farmers as decision makers into account. Each of the three components of the decision-making process, namely objects, rationales and outcomes (cf. Figure 1.1), lacks sufficient evidence including the links between them. Farmers' decision rationales depend on the characteristics of the objects of adoption. Objects and rationales for adoption in turn influence the final outcomes.

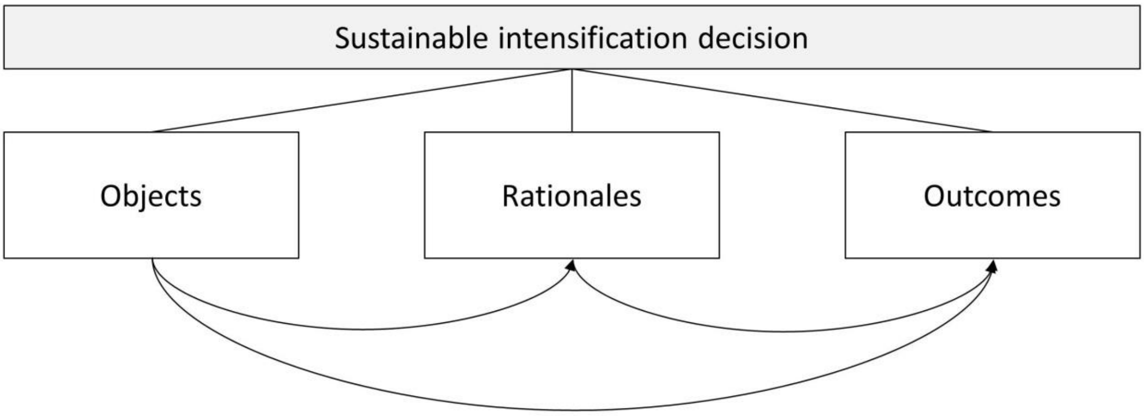


Figure 1.1 Framework for analysing the decision-making process for SI in this dissertation.
Source: Own representation.

We aim to contribute to the existing literature by comprehensively studying the links among SI measures, farmers' adoption behaviour and the resulting environmental outcomes and answer the following research question (RQ):

What can behavioural change of farmers through the adoption of sustainable intensification measures contribute to sustainable agricultural production systems?

To find an answer three sub-questions are analysed to take the SI decision process appropriately into account.

RQ 1: Which measures are subsumed under the sustainable intensification concept and how can regionally adjusted portfolios of sustainable intensification measures be identified?

RQ2: Which factors influence farmers' choices of sustainable intensification measures and are these choices interrelated?

RQ 3: How does the adoption of sustainable intensification measures affect farm environmental outcomes?

1.2 Research approaches

The empirical analyses of the three sub-questions are based on farm survey data from the northern German Plain from 2017 and qualitative data from the Rhinluch region (federal state of Brandenburg) from 2016. The latter was collected in focus group discussions and interviews with farmers, stakeholders from local and regional administrative bodies involved in land use and planning decisions, and representatives of nature protection organisations. The Rhinluch region is situated in and representative for the surveyed area in terms of being characterised by agricultural production in lowland peatland areas. Data collection took place within the EU H2020 ERA-Net Project *"Viable Intensification of agricultural production through sustainable landscape transition"*[2], running from May 2016 to April 2019. Thus the full decision process for sustainable intensification can be analysed using the same comprehensive data, reducing understanding bias. Likewise, results are not altered by regional specificities known to affect SI measures and outcomes (cf. Garnett *et al.*, 2013).

To study the research questions, theoretical and methodological challenges for each component of the sustainable intensification decision-making process have to be addressed. In the remainder of this section, we summarize the main reasoning for the research approaches chosen. Theoretical and methodological details, as well as further explanations on the studied area and data, are part of the empirical chapters (2–4) of this dissertation.

[2] Project webpage for more information: http://vital.environmentalgeography.nl/

Decision objects

The starting point to study farmers' adoption behaviour and outcomes of SI is to get a clear picture of the portfolio of measures from which farmers can choose. As existing SI definitions do not prescribe specific measures, we develop a conceptual model to obtain a generic understanding of SI measures. Following Meredith (1993), a conceptual model describes an event, object, or process based on existing knowledge. This is achieved by describing the content of the object under study as accurately as possible. Therefore, we collect, summarize and structure the measures and practices postulated as part of the SI concept in scientific research. A systematic literature review that allows processing large amounts of knowledge in a replicable and transparent way appears most appropriate (cf. Littell *et al.*, 2008). Systematic literature reviews have been increasingly used to explore research fields characterised by diverse views and multidisciplinary approaches. Examples include von Döhren and Haase (2015) for ecosystem disservices or Stechemesser and Guenther (2012) for carbon accounting. Gao *et al.* (2017) use this method with a similar purpose to this dissertation to achieve a practical definition of a generic concept, in their case for sustainable supply chain management.

The context-specificity of SI measures requires a procedure to translate the conceptual model of SI measures for the regional context of the subsequent quantitative studies. Following Franks (2014), regional solutions for SI rest on the place-based knowledge of stakeholders involved in land use. Therefore, transdisciplinary approaches involving stakeholders in the research processes become relevant. Mauser *et al.* (2013) frame the involvement of non-scientific experts in sustainability-related problems as essential to identify acceptable solutions for society. In focus group discussions with regional stakeholders involved in land use, we adjust the conceptual model to the context of the Rhinluch region, representative for the areas of the farm survey. However, a concise set of transdisciplinary methods has not been developed yet according to a literature review by Zscheischler and Rogga (2015). Therefore, to extend the validity of the procedure beyond the Rhinluch region, we repeat the process in three other European case study regions. In comparison to other transdisciplinary studies, the level of stakeholder integration in knowledge generation for this dissertation is comparably low and classified as ‘mutual one-way information’ according to Wiek (2007). To study decision rationales and outcomes, we refer to disciplinary approaches of agricultural economics.

Decision rationales

In agricultural economics farmers are the key group of agents whose decisions influence the spread of technological innovations or extent of agricultural land under conservation activities. Selecting an approach to analyse adoption behaviour requires accounting for a broad knowledge base. Determinants of adoption decisions, such as farm and personal characteristics, have been studied intensively (for overviews cf. Sunding and Zilberman, 2000; Knowler and Bradshaw, 2007; Foguesatto and Dessimon Machado, 2019). Still, the interpretation of patterns of decision determinants (cf. Burton, 2014), the inclusion of context-related information in decision models (cf. Wauters and Mathijs, 2014), and the development of holistic frameworks (cf. Carroll and Groarke, 2019) for decision-making remain under debate. In social psychology, behavioural factors are key modelling components. The Reasoned Action Approach (RAA), for instance, models decision-making based on behavioural beliefs of the decision-maker that shape attitudes, norms and the perceived control towards a behaviour, which in turn affect the behavioural intention (cf. Fishbein and Ajzen, 2011). The RAA or its predecessor the Theory of Planned Behaviour (Ajzen, 1985) have been applied in health (cf. Conner *et al.*, 2017) and consumer behaviour (cf. Fitzmaurice, 2005), and recently also in agricultural economics contexts (e.g., Senger *et al.*, 2017; Morais *et al.*, 2018). Behavioural factors have gained importance in studies on farmers’ decision-making independent of the underlying theory (Dessart *et al.*, 2019).

A further aspect to theoretically and empirically study decision rationales to use SI is that adopting is mostly related to choosing several measures. When multiple decisions are part of the implementation or adjustment of an agricultural system, these are likely to be taken in joint consideration and dependent on each other. There are some examples of studies capturing this aspect in terms of joint (e.g., Wollni *et al.*, 2010) and sequential decision-making (e.g., Sauer and Zilberman, 2012). We consider the interrelations in the decision for SI measures both in terms of the current use of SI measures and the intention to broaden the current portfolios of measures used. We also test whether positive experiences with related SI measures positively influence the intentions to adopt more SI measures in the future. The latter rarely enters decision models (cf. Yoder *et al.*, 2019).

To capture current use, future intentions, SI portfolio effects through experience, and behavioural factors with our existing cross-sectional data set, we rely on an explorative approach to study decision rationales. We choose a mixed-method approach with separate modelling stages for current SI portfolio choices based on multivariate probit models (cf. Kassie *et al.*, 2015a) and the intentions to broaden current portfolios based on partial least squares path models (cf. Reinartz *et al.*, 2009). In the latter, we focus on feedback effects in SI decisions through experiences with the current portfolio. Separating model stages provides a pre-step for integrative modelling (Hansson and Ferguson, 2011).

Decision outcomes

To identify the effects of using SI measures on farm outcomes, the sustainability outcomes of interest and their measurement need to be defined. For the northern European context of this dissertation with highly developed agricultural systems, environmental improvements through SI are most important (Garnett *et al.*, 2013). Still, the aspect that economic outcomes should remain at least stable cannot be neglected. In this regard, efficiency approaches are an established tool to assess the farm performance capturing multiple in- and outputs, including environmental outcomes (e.g., Areal *et al.*, 2012; Dakpo *et al.*, 2016). Inefficient farms could raise their outputs with the same amount and composition of inputs, or lower inputs while keeping output levels constant. This technical inefficiency of the farm is measured by the distance of current farm production to a production possibility frontier (Bogetoft and Otto, 2010).

Eco-efficiency approaches dating back to Schmidheiny (1993) focus exclusively on the trade-off between economic outputs and positive or negative environmental outcomes of production. Multiple examples of eco-efficiency analyses for agricultural economics exist (e.g., Picazo-Tadeo *et al.*, 2011; Gómez-Limón *et al.*, 2012; Pérez Urdiales *et al.*, 2016). Data Envelopment Analysis (DEA) is frequently applied to measure the distance to the eco-efficient frontier as formally introduced by Kuosmanen and Kortelainen (2005).

With DEA the eco-efficient frontier is determined by the best performing decision-making units in the sample and all units are benchmarked against this best-practice frontier. As SI poses different restrictions in terms of agricultural practices and input use, it is likely that SI adopters and non-adopters face different production possibility sets (PPS) and frontiers. Beltrán-Esteve and Reig-Martínez (2014) demonstrate the distinction of PPS according to the production system when comparing the efficiency of organic and conventional farms. The two frontiers are enveloped by a meta-frontier. The meta-frontier approach and the separation of managerial efficiency, i.e. performance within the own technology, and program efficiency, i.e. the distance of the sub-frontier to the meta-frontier, date back to Charnes *et al.* (1981).

Using directional approaches of benchmarking, the distance from farm production towards the frontiers can be measured in any direction (Picazo-Tadeo *et al.*, 2005). For this dissertation, we consider the direction of the environmental outcome while keeping the economic outcome level constant. Following Asmild and Hougaard (2006) and Asmild *et al.* (2016), the distance to the meta-frontier represents an improvement potential for farmers. The success of SI measures is determined by how much these reduce the improvement potential in the direction of the environmental output.

Comparing the differences in observed improvement potentials between SI adopters and non-adopters does not suffice to causally identify the environmental improvement through SI adoption. The observed differences can be confounded by structural differences in farm(er) characteristics. To capture the causal effect of SI adoption on an individual level would require measuring both outcomes for the cases of adoption and non-adoption, but one is not observable. When the assignment to treatment and control groups is not random but subject to the decision of the farmer, the comparison of average outcomes between groups will also lead to biased results (cf. Rubin, 1974). This self-selection bias occurs when the selection into treatment, in the context of this dissertation the adoption of SI measures, is based on the perceived rewards or outcome of this decision.

In non-experimental designs, which prevail in the social sciences, a variety of methods exists to reduce the self-selection bias, such as matching or control function approaches (cf. Blundell and Costa Dias, 2009). The use of matching approaches has been recently shown to be advantageous for the causal interpretation of differences in efficiency scores (cf. Bogetoft and Kromann, 2018). Therefore, we generate a control group of non-adopters that resembles the SI adopters in all relevant characteristics as a counterfactual. Relevant characteristics for matching include all variables that potentially influence adoption and the outcome. Then the assignment to treatment can be treated as if being random (cf. Dehejia and Wahba, 2002). For the identification of effects and the selection of relevant variables, a theory on the data generation process is necessary (Elwert and Winship, 2014). For this dissertation, the theoretical model of Chabé-Ferret and Subervie (2013) on farmers' decisions for agri-environmental schemes (AES) and the related outcomes is adjusted to frame adoption and eco-efficiency outcomes of SI measures.

1.3 Contributions and structure of the dissertation

Subsequent to the introduction highlighting the research needs, questions and approaches, this dissertation consists of three analytical chapters and a final discussion *(Chapter 5)*. Each analytical chapter centres around one of the three research sub-questions and takes up the one from the preceding chapter. The initial study presented in *Chapter 2* lays the analytical foundation by structuring the main SI measures discussed in the scientific literature in a conceptual model. This model allows determining regional SI solutions through a transdisciplinary stakeholder process. In *Chapter 3*, we analyse farmers' motives in choosing and optimising portfolios of SI measures. We focus on the role of interdependent decision-making through experience among currently used SI measures and intentions to broaden the portfolios of SI measures in the future. The approach acknowledges the regional selection process to determine relevant SI measures for the study. The analysis in *Chapter 4* focuses on improvements in farm environmental efficiency outcomes through SI accounting for the decision rationales of farmers to self-select into the group of adopters. The structure of the dissertation and the interplay of research questions, foci of analysis and the publication status of results in peer-reviewed journals is summarised in Figure 1.2. Subsequently, we provide a short of summary of each chapter.

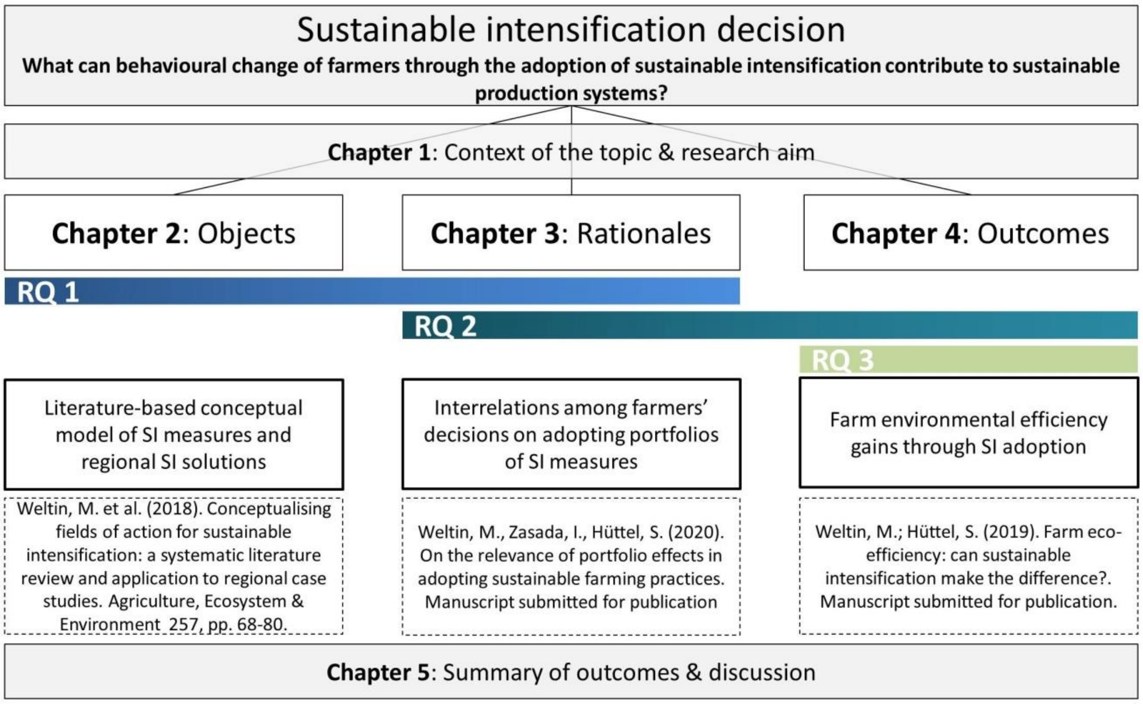


Figure 1.2 Overview on the structure of the thesis, outcomes of empirical studies and related research questions.
Source: Own representation.

In ***Chapter 2***, we comprehensively explore the academic SI literature and propose an implementation-oriented conceptual model of SI measures. A systematic literature review of 349 papers from 1997 to 2016 captures temporal, spatial and disciplinary trends and depicts the most relevant SI measures. The developed conceptual model clarifies the decision objects of SI by differentiating four fields of action and 26 groups of SI measures. Its applicability to derive region-specific SI solutions is demonstrated through stakeholder processes in four European case study regions. The main findings are that disciplinary boundaries and different temporal and spatial strands in the literature prevent a holistic view of SI in the scientific discourse. This leads to the dominance of research describing SI measures in isolation. Combining multiple SI measures and coordinating actions beyond the farm scale is comparatively underrepresented. In the investigated case studies, however, farmers and stakeholders defined regionally adjusted sets of SI measures including agronomic and technological interventions on the farm as well as approaches of landscape planning and regional integration beyond the farm scale.

The chapter rests on the publication *Weltin et al. (2018b). Conceptualising fields of action for sustainable intensification – a systematic literature review and application to regional case studies. Agriculture, Ecosystems & Environment, 257, 68-80.* We presented a preliminary version of the results at the XV Congress of the European Association of Agricultural Economists in Parma (Italy) and the Annual Conference of the German Association of Agricultural Economics in Freising (Germany) both in 2017.

The analysis in ***Chapter 3*** deals with the interrelations in the decisions of farmers to use a portfolio of five SI measures for the northern German Plain to fully exploit ecological improvement potentials. The SI measures have been selected and prioritised in the stakeholder process in the Rhinluch region. Unclear interrelations of measures, uncertain benefits and cost ratios make the adoption decision complex. In this chapter, we focus on decision rationales and the interrelation of current use and future intentions to broaden adoption of SI practices through experience with the currently used SI portfolio. We first investigate complementarity of locally adjusted measures in a multivariate probit model, where we find support for positive reinforcements of adoption decisions. Second, we use an explorative path modelling approach and find perceived economic and environmental benefits of applied practices to be positively related to farmers' intentions to adopt additional complementary practices. We discuss how these paths can serve as a base for developing integrated modelling approaches required to develop intervention schemes to foster large-scale adoption of sustainable farming practices.

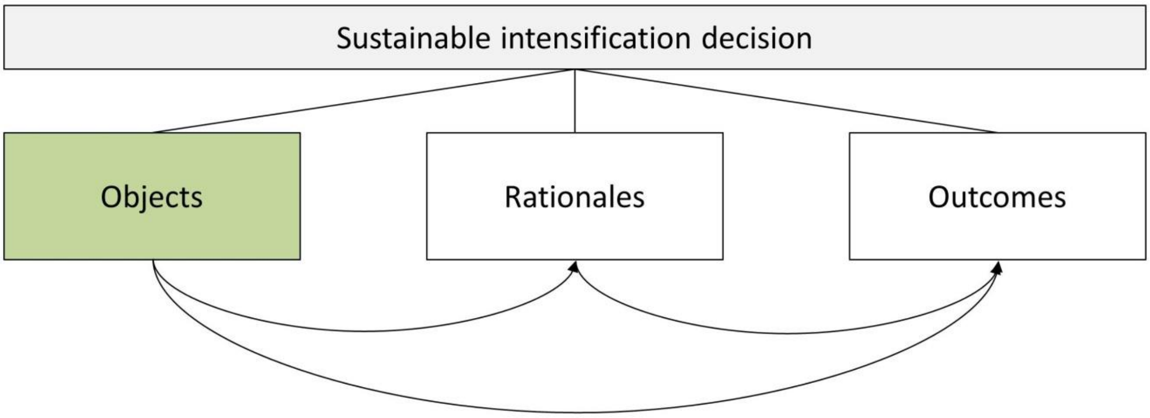
The chapter rests on results submitted for publication and currently under peer-review. We presented a preliminary version of the analysis at the 3rd International Conference on Global Food Security in Cape Town (South Africa) in 2017, the 30th International Conference of Agricultural Economists in Vancouver (Canada) and the 13th European Farming Systems Symposium in Chania (Greece) both in 2018.

The aim of the analysis in ***Chapter 4*** is to test the on-farm outcomes of using SI measures. We empirically investigate the extent of the ecological improvement potential on farm level based on eco-efficiency. Thereby, we assess and quantify the decision outcomes of SI. Farms applying SI measures should be able to produce at a higher ecological efficiency without losses in economic efficiency. A directional non-parametric meta-frontier approach allows us to determine the system frontier and respective farm eco-efficiency scores. We build a theoretical model to account for selectivity issues and base the efficiency analysis on a matched sample for the adopters and non-adopters of SI measures. We use a biodiversity indicator as a measure for the ecological outcome and apply our approach to the farm survey data from the northern Germany plain. The results show that the SI adopters largely determine the system frontier. A comparison of the scores in ecological direction between the adopters and non-adopters shows higher mean eco-efficiency, even though most adopters do not fully exploit their farms' ecological improvement potential.

The results of this chapter are based on a study submitted for publication and currently under peer-reviewed. We presented an earlier version of the results at the Eco-efficiency Workshop of the DFG Research Unit FORLand at the University of Natural Resources and Life Sciences Vienna in 2018.

Chapter 5 includes a summary and joint discussion of the key results of the empirical chapters 2–4 to answer the overarching research question. A central point is that the decision-making of farmers needs to be acknowledged to understand SI outcomes and identify how future improvements can be reached. We discuss the methodological and theoretical contributions of the dissertation and consider the policy implications that result from the empirical results. From this discussion, we finally derive future topics and directions of research.

2 Conceptualising fields of action for sustainable intensification: a systematic literature review and application to regional case studies



This chapter is based on the following article:

Weltin, M., Zasada, I., Piorr, A., Debolini, M., Geniaux, G., Perez Moreno, O., Scherer, L., Tudela Marco, L. and Schulp, C.J.E. (2018). Conceptualising fields of action for sustainable intensification–A systematic literature review and application to regional case studies. Agriculture, Ecosystems & Environment, 257, 68-80.

2.1 Introduction

Responding to increasing global food demand, food production has kept pace so far through agricultural expansion and intensification (FAO, 2009; Tilman *et al.*, 2011; Stevenson *et al.*, 2013). Future prospects are, however, controversial. Whereas some estimate further increases in food production (Ewert *et al.*, 2005), others assume stagnating or decreasing crop yields due to the limited and increasingly degraded land and natural resource base and impacts caused by climate change (FAO, 2009; Ray *et al.*, 2012; Stevenson *et al.*, 2013; Eitelberg *et al.*, 2015).

Against this background, the notion of sustainable intensification of agriculture (SI) has received growing attention in its ambition to simultaneously tackle food security and environmental challenges. In the last two decades, SI research has shown manifold new paths on how to combine the maintenance or increase of agricultural production (Garnett *et al.*, 2013; Röös *et al.*, 2017) on the same area of land (Godfray *et al.*, 2010) and the contribution to sustainable development in a balanced way (Gadanakis *et al.*, 2015). However, with rising popularity, the scope and objectives of SI have been increasingly widened due to the variety of disciplinary perspectives, suggested SI practices and geographical foci of interest. SI embraces a broad range of practices and contexts, including smallholder agriculture in developing countries and agro-ecological principles as well as the application of new technologies and management styles (Baulcombe *et al.*, 2009; Foresight, 2011). Further research foci have been set on technological advances and the assessment of SI from a global perspectives (Baulcombe *et al.*, 2009; Tilman *et al.*, 2011), the resilience and durability of production (Dile *et al.*, 2013; The Montpellier Panel Report, 2013) as well as better knowledge of the production process (Buckwell *et al.*, 2014). In line with these developments, SI has been connected to the provision of ecosystem services and economic, social and ethical aspects of sustainability (Barnes and Poole, 2012; Garnett and Godfray, 2012; Smith, 2013) or to the generation of multiple benefits. Godfray (2015) also highlight the role of SI for changing the food system as a whole, which includes questions of food supply chains, consumption pattern and food waste and losses.

Accordingly, controversies persist regarding the understanding of the scope and scale of sustainability or environmental goals (Buckwell *et al.*, 2014; Petersen and Snapp, 2015), the extent of the environmental benefits generated, and negative effects mitigated (Pretty, 1997b; Baulcombe *et al.*, 2009; Garnett *et al.*, 2013) or compensated elsewhere (Franks, 2014). The latter case even allows for intensification in some locations if associated negative impacts are counterbalanced by positive environmental impacts at another place. Given the need for action to simultaneously address issues of food security, increasingly limited natural resources (Cordell *et al.*, 2009), environmental degradation (Smith *et al.*, 2016), and climate change adaptation (Thornton and Herrero, 2015), more emphasis on the elemental principles of SI, namely the aspiration to increase food production on less environmental costs, is essential. Rather than a specific practice or set of practices, SI constitutes this aspiration as a goal (Garnett *et al.*, 2013). Stronger orientation on implementation is needed, which in turn requires consideration of the regional and situational context the selection and application of SI practices depends on (Godfray and Garnett, 2014). Therefore a clear and unbiased framework for the selection is required. In this regard, an acknowledgement and systematic structuring of the various ideas on SI implementation found in the scientific literature can support decision-making in practice and simultaneously contribute to a tangible conceptual understanding of SI.

Based on a systematic literature review, the objectives of this chapter are (1) to comprehensively explore the SI literature and provide a structured analysis of the diversity and scope of SI research and knowledge, (2) to propose an action-oriented conceptual framework on the basis of the portfolio of existing SI practices, and (3) to demonstrate its applicability to identify SI practices for region-specific problem settings in selected European case studies using a participatory stakeholder process. Thereby this chapter provides answers to the dissertation's ***research question 1***: *Which measures are subsumed under the sustainable intensification concept and how can regionally adjusted portfolios of sustainable intensification measures be identified?*

Findings concerning the three objectives of this chapter are provided in separate sections (2.3 to 2.5), resulting in one proposition per objective, which are then resumed, discussed and connected in Section 2.6.

2.2 Methodology

We have carried out a systematic review of the existing literature in the field of sustainable intensification to obtain an interdisciplinary and comprehensive overview of the topic (cf. von Döhren and Haase, 2015; Gao *et al.*, 2017). Subsequently, we intertwined the review with the development of a conceptual framework of SI practices. First, the materials for analysis were selected by using the two main collections of academic literature, the Scopus database (www.scopus.com/) and Web of Science (https://webofknowledge.com/*)* (Aghaei Chadegani et al., 2013; Harzing and Alakangas, 2016)*.* We applied the search term 'sustainable intensification' in title, author keywords or abstract for all research articles and review papers, which had been published before December 31st, 2016. In doing so, we deliberately captured only literature that focuses closely on SI. Our final database was composed of 349 papers. The overlap of the two sources of literature comprises 271 articles, 59 are exclusively collected by Scopus and 19 by Web of Science respectively. Each article's meta data was recorded. This included the year of publication, keywords, the publishing journal, and both internal citations by other articles within our article sample (available for Scopus data only) and external citations in articles which are beyond this SI literature. We also included the geographic coverage for systematic analysis using information from abstracts and keyword search. All retrieved information was descriptively evaluated.

For a systematic description of the content of the selected papers, categories for analysis need to be defined in accordance with the research aim (Brewerton and Millward, 2001; Harkonen *et al.*, 2015). In categorizing, we addressed the practical implementation of SI in three taxonomic layers. The bottom is built by the concrete, practical actions an actor takes to implement SI which we collected from abstracts and conclusions of the articles. We refer to them as SI *practices* throughout the chapter. Due to their diversity, the single SI practices are summarized in bundles of similar practices making up general SI *approaches*, our second taxonomic layer. As a third layer, four categories were derived from two discriminating dimensions namely spatial scale and activity scope of SI. The identified SI approaches were assigned to the categories named *fields of action* (FoA) for SI. They are the basis for a conceptual framework of SI. We collected 646 SI practices in the 349 articles which we summarized in 26 SI approaches.

Although to some extent personal valuation guides assignment to the four FoA, the consistency of the final solution was verified by multiple rounds of cross-checks by researchers from different disciplines (incl. economics, geography, natural resource management, agricultural sciences). Details on the final database are available through an additional data publication provided in Appendix A of this dissertation.

The applicability of the framework to specific regional problem settings was tested in four regional European case studies through participatory processes with in total 68 stakeholders involved in land-use decisions (agriculture, administration, environment, research). Case study regions were selected in order to capture a variety of geographical contexts, land use and landscape characteristics following van der Zanden *et al.* (2016). The participatory methodology was selected as a useful tool for the production of region-specific knowledge from the direct involvement of key stakeholders in the diagnosis of SI implementation (Kemmis *et al.*, 2014). We drew on the methods of Reed *et al.* (2009) and started the fieldwork with in-depth interviews with farmers and other stakeholders relevant for implementing SI practices followed by a snowball sampling to identify the stakeholders that are part of each agrarian system. The second phase of the analysis was the organisation of a participatory workshop in the four European case studies. Methodological guidelines were elaborated to ensure that the workshops enabled the cross-comparison of the results. The main objectives of the workshops were: (i) to present to the stakeholders the four FoA stemming from the SI conceptual framework, (ii) to discuss the SI practices that are currently applied, commonly categorizing them into the four FoA; and (iii) to stimulate stakeholders to share their understanding of possible future SI practices for their region. Results on current and future SI practices were descriptively evaluated and compared across regions.

2.3 Scope of the SI literature

2.3.1 Development of the SI literature

Initially introduced by Pretty (1997b), the SI literature can be divided into three phases reflected by the temporal and geographical development of publications (Figure 2.1). It originated in parallel to the mainstreaming of sustainability initialised by the Brundtland

Report (1987) and the rise of the ecosystem service concept (Costanza *et al.*, 1997; Daily, 1997), bringing environmental emancipation into the economic domain (e.g., Goodland and Daly, 1996). In a first phase (1997-2008), SI evolved to mainly explore the possibility to support smallholder agriculture and livelihoods in Africa, Asia and Latin America while generating environmental benefits (Clay *et al.*, 1998; Shiferaw and Holden, 1998). Research in this phase focussed on the improvement of underutilised land, the role of local knowledge and embeddedness in local social networks and institutions (Bebbington, 1997; Pretty, 1997b). The first three years resemble a kick-off for SI research with 11 publications, which was later largely marginalised between 2000 and 2008.

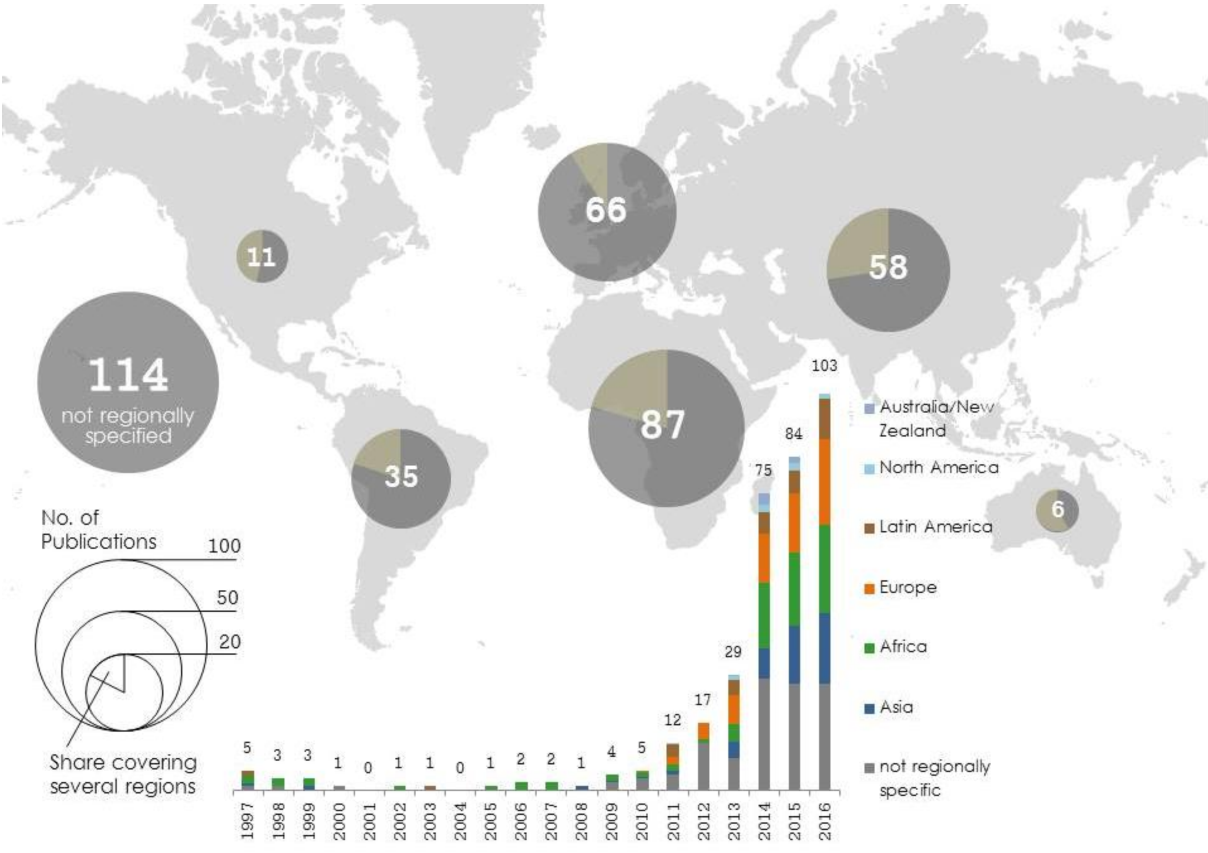


Figure 2.1 Geographical and temporal distribution of published studies (N=349).
Source: Own representation.

After the food price crisis in 2007/08, the number of SI publications showed an increasing trend, accompanied by a growing and robust body of evidence on environmental degradation and biodiversity loss due to agriculture (MEA, 2005) and the intensifying research on climate change (McCarthy *et al.*, 2001; Parry *et al.*, 2007). The second phase of the SI research (2009-2013) was complemented by resource efficiencyoriented and technology-related publications (Balasubramanian *et al.*, 2007; Flavell, 2010). Emphasizing the need to produce 'more food on a sustainable basis with minimal use of additional land' (Baulcombe *et al.*, 2009), they highlighted a great need for innovation, the application of new technologies and the insights of biological and crop science, including breeding and genetic improvements (Foresight, 2011). SI slowly gained renewed resonance in other parts of the world, particularly for the intensive European agricultural systems. This also included advancements in indicator developments for the assessment of trade-offs between economic and environmental objectives of agriculture (Geniaux *et al.*, 2009). However, in North America as well as in Australia and New Zealand, the term 'sustainable intensification' had hardly entered the scientific literature.

The third most recent phase of the SI research (2014-2016) was characterised by a rapid expansion of research and publication activities focussing on farming systems around the world. These three years alone covered 75% of all reviewed publications and are accompanied by a further widening of the discussed topics. However, after the sharp increase of publications on SI in the year 2014 (+159%), growth has been slowing down again in 2015 (+12%) and 2016 (+23%). Recent literature stressed that SI can only be a part, albeit an important one, of multidimensional strategies to achieve food security (Godfray and Garnett, 2014; Davis *et al.*, 2016) and resilient agriculture within a globally sustainable future (Rockström *et al.*, 2016). Additional to the scientific literature, the notion of SI has increasingly entered the political domain, as it has been part of the reform process of the European Common Agricultural Policy (CAP) because of the commissioning of the RISE report on SI implementation and evaluation with a clear policy horizon (Buckwell *et al.*, 2014).

2.3.2 Systematic appraisal of the SI literature

The keywords of articles, which authors use to indicate the focus of their work or to connect it to other scientific strands of literature, provide a first insight into the wide diversity of topics covered by the SI literature. Overall 937 different keywords were used in the selected publications. More than one third of the articles (39.5%) use the term 'sustainable intensification' in keywords. Searching for commonalities in the SI research, we found however that there is no keyword unifying a very large share of the articles.

The diversity of keywords can already be represented by analysing those 27 keywords that make up the first quartile of all keywords ordered by highest use. They are used in at least six articles equal to only 1.7% of publications (Figure 2.2a). The most frequent keyword other than 'sustainable intensification' itself is 'food security', which relates to one of the main aims of SI (Pretty, 1997b) and is only used by 14.9% of the articles. It is followed by 'ecosystem services' (7.7%), another important research strand (Costanza *et al.*, 1997; MEA, 2005), underlining the influence of ecosystem services research on SI research. Keywords describing how SI should be achieved indicate a broad scope for implementation. They include 'intensification' as well as 'agro-ecology' or 'conservation agriculture', which are frequently formulated as a contradiction to the former (Marsden, 2010), and range from 'land sparing' for conservation activities to closing 'yield gaps' and 'technology adoption'.

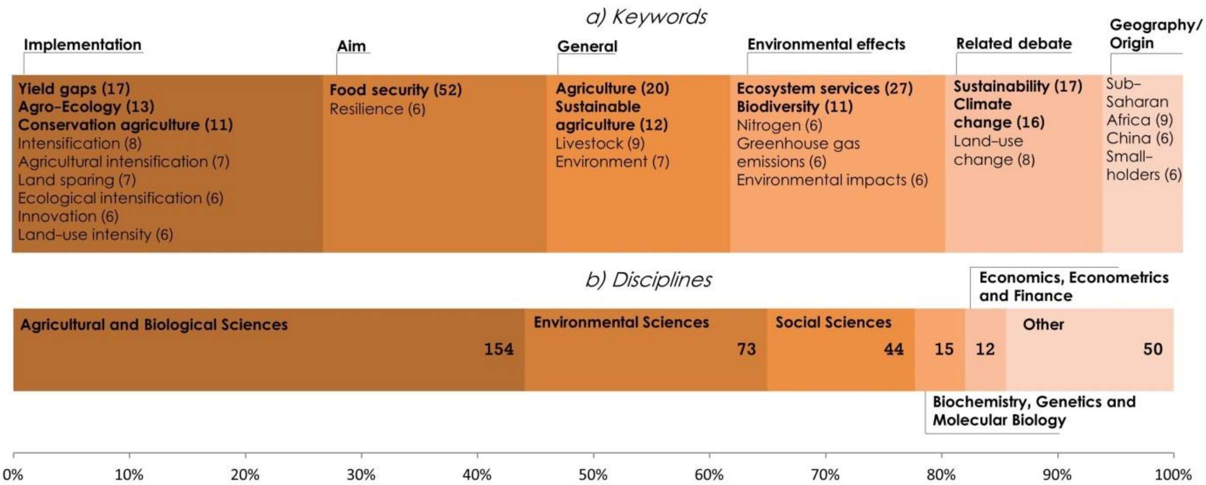


Figure 2.2 Thematic focus of the selected articles (N=349).
Note: Represented by (a) most frequently used keywords (min. six times, singular and plural versions were counted as one keyword, the 10 most frequent keywords are marked in bold) and (b) scientific discipline of the journals. Categorization of disciplines based on Scimago Journal and Country Rank portal's classification of subject areas http://www.scimagojr.com/. Category "other" contains 5 journals not listed. Publications with several disciplines contribute in equal shares to each of them.
Source: Own representation.

The SI literature spreads across diverse research areas and journals. The articles were assigned to their main scientific disciplines. The selected papers were published in 176 journals and cover 22 disciplines with agricultural and biological (44%), and environmental sciences (21%) enjoying predominance (Figure 2.2b). In comparison, SI is underrepresented in the social sciences and in economics, which are key to discussing how relevant actors can be incentivized to adopt SI practices.

As measured by the number of absolute citations, both within the sample of SI literature and outside by other scientific articles (Figure 2.3, for Scopus data only), there are few SI publications with very high impact, also considering the fact that the majority of the papers are published between 2014 and 2016. The number of external citations measures the attention that the literature receives for questions beyond the core of SI.

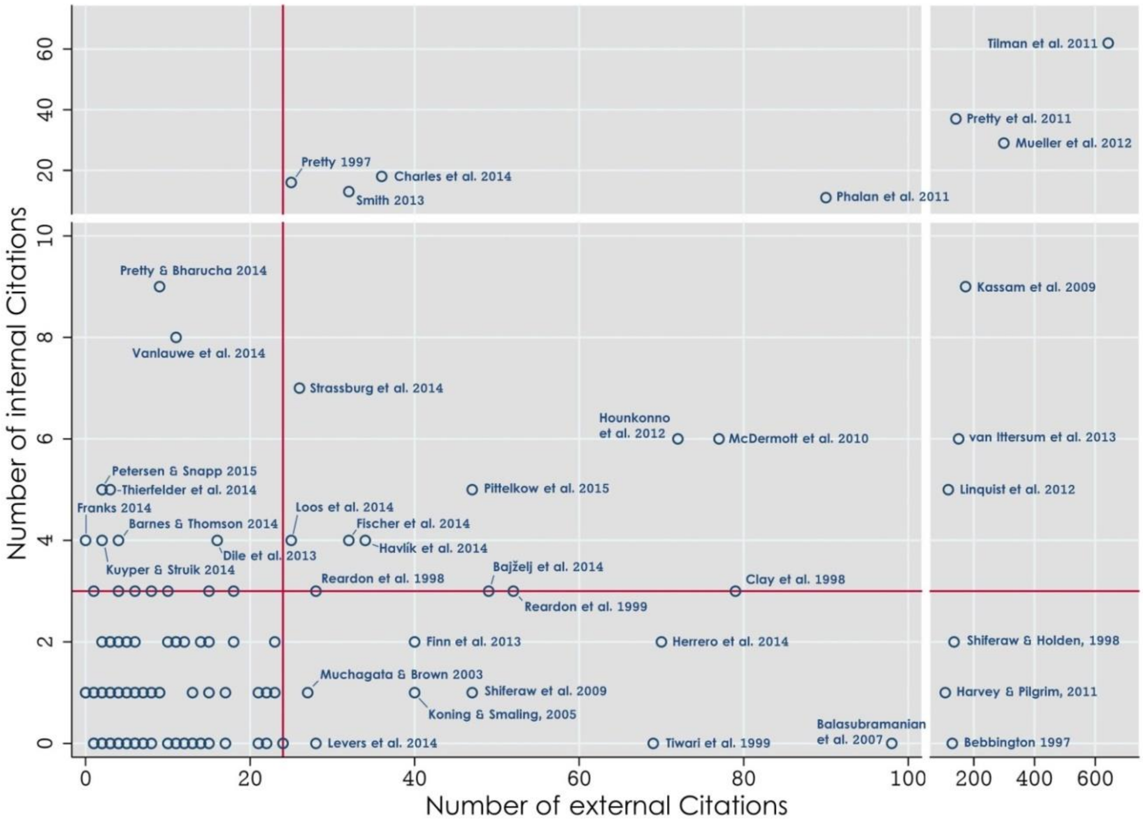


Figure 2.3 Relationship of external and internal citations in the analysed literature.
Note: Based on Scopus database and citation records (N=330). Red lines represent the 90% quantiles of the respective axes. The citations of 194 articles do not exceed both quantiles. 96 papers are not cited and, therefore, excluded.
Source: Own representation.

The number of citations within the selected publications identifies the key contributions to the SI literature. Whereas 96 papers are not cited at all (70% of them are recently published in 2016), only 40 papers have more than either 3 internal or 24 external citations (90% quantiles). 37.5% of these were published between 2014 and 2016. The 40 papers can be again separated into three groups: those which are exclusively relevant for the internal or external literature (8 and 15 respectively), and those which are highly appreciated by both (17).

Citation records range up to 182 for external citations and 18 for internal citations except for three outliers. These three papers (Pretty *et al.*, 2011; Tilman *et al.*, 2011; Mueller *et al.*, 2012) show a rather outstanding position. With the development of African agriculture (Pretty *et al.*, 2011), greenhouse gas emissions and global nitrogen use in different agricultural production scenarios (Tilman *et al.*, 2011) and yield gaps (Mueller *et al.*, 2012), these papers cover frequently addressed topics in the SI literature, but are also of interest for non-SI research. Other highly relevant contributions discuss particular SI approaches such as conservation agriculture (Kassam *et al.*, 2009) and land sparing (Phalan *et al.*, 2011a).

Looking at the publications of internally high impact, measured in high citation records, the literature concentrates around the last five years. Only three publications above the internal 90%-quantile are older. From the initial phase of SI literature (1997–2008), only Pretty (1997b) with 16 internal citations has been internally cited more than three times. This indicates a thematic shift with a marked disconnection of the subsequent SI research from the initial literature. Although the initial publications are of little relevance for the sample of SI literature internally, they are fairly well recognized externally. Additionally, no unifying paper for the SI research stands out. Comparably relevant articles that discuss the multitude of SI approaches in several systems (Pretty and Bharucha, 2014; Vanlauwe *et al.*, 2014) are only cited by around 5% of subsequent articles.

Summarising our observations on the SI literature, we find temporal phases of stagnation, revival and sharp rise with different foci indicating thematic breaks alongside other parallel research topics. The uptake started at different times in different world regions and some are still neglected. Wide spread of related topics and keywords, broad but unbalanced disciplinary coverage and rather loose internal connection point towards high diversity and complexity of the topic. This leads us to the first *proposition (2.1)*, that heterogeneity in perspectives from which SI is discussed exists. A systematisation is required for a more integrated understanding of the existing knowledge on SI and the identification of existing research gaps.

2.4 Conceptual framework: Fields of action for sustainable intensification

2.4.1 Differentiating SI dimensions

To support conceptual development, a procedure based on practical implementation of SI was chosen. Corresponding to the heterogeneous SI research, a broad and diverse portfolio of SI practices was identified in the selected articles. We distinguish SI practices according to (1) the spatial scale whether they are carried out at a farm or landscape level, and (2) the activity scope from a land-use to structural optimisation, as these dimensions have been chosen as scaling issues (Gunton *et al.*, 2016). Land use (Phalan *et al.*, 2011b), structural adjustments of production system and efficiency approaches (Pretty and Bharucha, 2014) are frequently discussed in the literature to differentiate the notion of SI.

Spatial scale of SI: Farm and landscape level

Like agriculture and land-use management in general, SI approaches are very much scale-dependent. Certain practices, mainly related to agronomy and input efficiency, are predominantly limited to the field and farm level. For those SI practices, the farm system represents the entity for which processes and outputs are optimised. SI practices are usually implemented by individual innovative changes on the farm, such as new breeds or cropping patterns or farm management tools. On the farm level, SI practices are also stimulated through regular agricultural extension services, environmental regulations and standards or public policies (World Bank, 2007; Avolio *et al.*, 2014). Other practices require consideration of the situation beyond the farm gate. Their implementation and effects depend on the scales of the ecological and human systems they are interacting with (Ferreyra *et al.*, 2008; Duru *et al.*, 2015), which usually manifest at regional and landscape or watershed level (Lefebvre *et al.*, 2015). The research about land sparing and land sharing and their contribution to biodiversity is, for example, very scale-dependent either segregating areas for production and conservation at larger scales versus integrated on-site conservation efforts (Phalan *et al.*, 2011b). Other SI approaches draw on the value added, which is generated through the pro-active embeddedness of the farm into the larger regional context, e.g. through coordinated actions, cooperation in supply chains or knowledge exchange (Hinrichs, 2003; Morgan, 2011). Due to the multitude of actors, stakeholders and farmers involved, the implementation depends on spatially coherent and well-functioning institutions and governance structures to cope with the complexity of regional conditions and requirements, social interactions, conventions and interests (Armitage *et al.*, 2012; Zasada *et al.*, 2017).

Activity scope of SI: Land use and structural optimisation

The SI literature covers a broad set of very different practices (Pretty and Bharucha, 2014) depicted in the activity scope – either focussing on land-use or structural aspects. The former is closely linked to agricultural and agronomic questions of practices related to changes in cultivation and livestock rearing as well as to land use and landscape planning. The latter relates to strategic planning and organisation of production processes, inputs and resource use at the farm and beyond as well as interactions and exchange among actors. Regarding the optimisation of land use, SI practices include the use of novel or more environmentally effective practices of cultivation and livestock rearing (Foresight, 2011), e.g. precision farming or crop-livestock integration as well as targeted decisions on the purpose land should be used for depending on its site characteristics and functions (Coyle *et al.*, 2016). However, it was shown that resource use efficiency assessments are affected by whether or not they include environmental outputs (Areal *et al.*, 2012). Therefore, another angle from which to address the activity scope is the use of resources such as natural and non-renewable inputs, labour and knowledge, both on the farm and beyond. Management of all available resources including human resources increase productivity, reduce non-renewable input use and enable the regional exchange of knowledge and resources (Buckwell *et al.*, 2014; Loos *et al.*, 2014). Investments for the improvement of human capital and efficient resource use are well-known success strategies to create synergies between economic development and environmental sustainability (Goodland and Daly, 1996). This perspective of SI focusses on the management cycle of production and implies a structural optimisation. Land use and structural optimisation form the endpoints of a gradient that determines the activity scope of SI. Practices can share aspects of both such as precision farming, which is a new technology especially spatially-targeted to apply inputs efficiently.

2.4.2 A conceptual framework of sustainable intensification

The combination of the two dimensions of spatial scale and activity scope of SI establishes four fields of action (FoA) that unify SI practices and approaches and represent the baseline of an action-oriented conceptual framework of SI that integrates the heterogeneous literature. According to the SI practices and approaches assigned to the FoA, we label the fields of action FoA I 'Agronomic Development', FoA II 'Resource Use Efficiency', FoA III 'Land Use Allocation', and FoA IV 'Regional Integration'. Figure 2.4 provides an overview of the FoA, the assigned SI approaches including the number and share of mention in the articles.

Agronomic Development (FoA I)

A majority of practices (N=234; 36%) are closely related to questions of agronomic development, either dealing with the cropping system, or to a lesser degree also with the livestock system. In order to reach agronomic objectives, such as increasing land productivity, crop yields and quality as well as sustainability goals, optimising cultivation methods or production techniques are proposed. Among the approaches, there is a clear focus on adapted cropping (N=72; 33%). This includes crop rotations where cultivated crops directly impact the health status of succeeding crops and indirectly support them via the soil's physical and nutrient status. Intercropping and cropping pattern diversification utilise these effects by allocating preceding crops temporally targeted, while mixed cultures, strip cultivation, agri-horticultural or agroforestry systems allocate beneficial effects spatially targeted (Hellin *et al.*, 2013; Mao *et al.*, 2015; Nyagumbo *et al.*, 2016).

Within a specific crop management system, practices embrace choice of variety and crop management including techniques from tillage to soil conservation (Giller *et al.*, 2015; Townsend *et al.*, 2016). Using practices of biotechnology and genetic engineering is more frequently mentioned (N=32; 14%) than conventional breeding (N=27; 12%), given their potential for crop yield and quality increase with improved resistance against water stress or pests and diseases. However, legal restrictions are also pointed out (Raybould and Poppy, 2012; Beaudoin *et al.*, 2014; Harrison *et al.*, 2014).

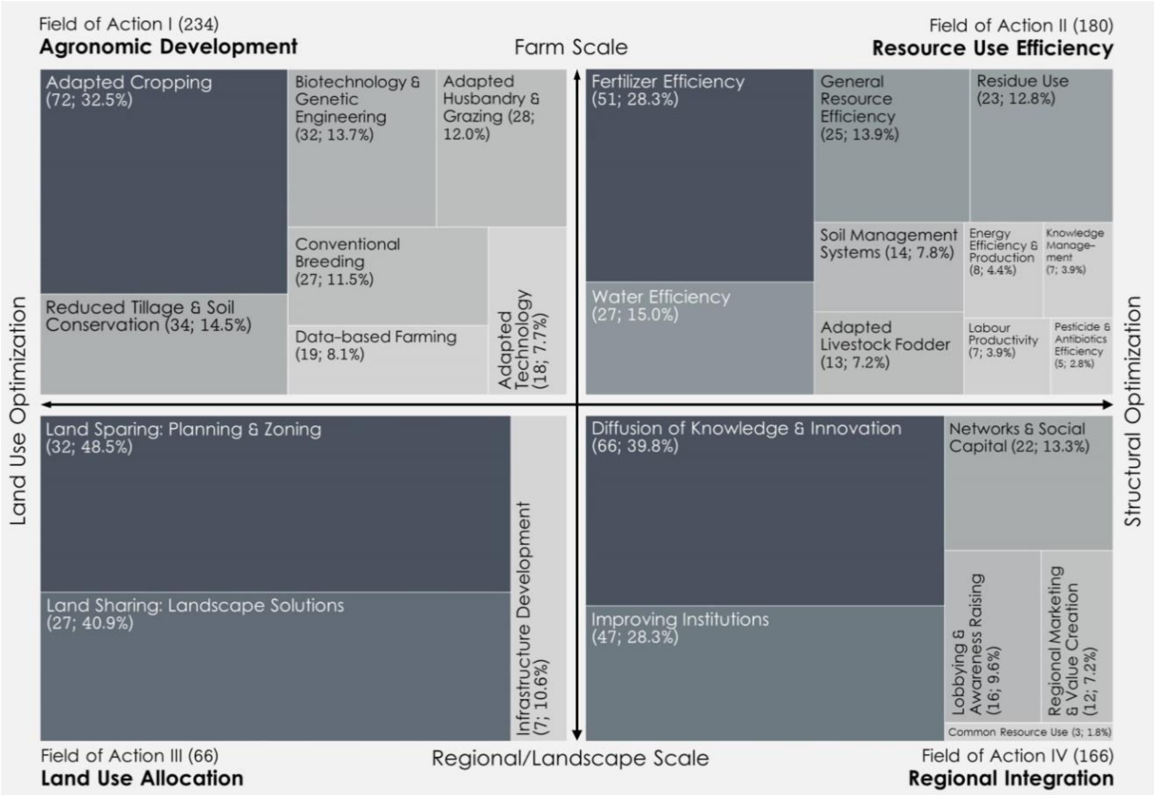


Figure 2.4 Conceptual framework of SI: Fields of Action, related SI approaches as described in the 349 selected articles.
Note: One article can address several SI approaches. In parentheses: Frequency of an approach; Share of approach within FoA. Box sizes correspond with the frequency of occurrence in the literature. Source: Own representation.

The strong interconnection of novel technical solutions, new digital technology applications and the use of site-specific information and system data are characteristic of first implemented 'smart' agronomic system solutions (Kidd, 2012; Ball *et al.*, 2016), and the ongoing discussions towards future agronomic systems. Precision farming takes a central position here, as it allows for site-specific optimisation of cultivation, and is hence applicable both to intensive integrated (conventional) as well as organic farming systems (Gumma *et al.*, 2016). Despite the development and existence of similar system approaches in husbandry, scholars rarely contextualise those in the frame of SI (Szabó and Halas, 2012). Our literature review mostly identified adapted grazing systems (N=27; 12%; rotation, density management).

Resource Use Efficiency (FoA II)

SI practices in the second FoA (N=180; 28%) circulate around approaches to efficiently handle the available natural, chemical, and human resources of an agricultural holding to reduce agricultural expenses, and/or environmental pressures. These papers highlight pathways to increased agricultural productivity by either using fewer inputs (resources) or producing more outputs. Natural resources include irrigation water, manure, residues and animal feed, while chemical resources include fertilizers and pesticides, and human resources encompass labour, knowledge and managerial abilities. The major approaches related to resource use efficiency found in the scientific literature relate to fertilizers (N=51; 28%), residues (N=23; 17%) and water (N=27; 15%). In contrast, approaches associated with human resources, such as knowledge management and labour productivity are less frequently covered by current SI research.

Articles cover novel techniques of nutrient management practices to improve fertilizer efficiency (Suter *et al.*, 2015; Wani *et al.*, 2015) as well as measurements of related carbon, nitrogen, and phosphorus balances and losses (Linquist *et al.*, 2012; Zhou and Butterbach-Bahl, 2014; Sattari *et al.*, 2016). Irrigation has been examined as contributor to water scarcity and ecosystem damage, which is particularly relevant in drought-prone regions (Scherer and Pfister, 2016). Papers that outline methods for increasing water use efficiency were focussed on topics like marginal water use, integrated crop water management (Jägermeyr *et al.*, 2016) or rainwater harvesting (Dile *et al.*, 2013). Further, pesticide and antibiotics use (Ellis *et al.*, 2016) and energy efficiency and production (Krupnik *et al.*, 2015) are relevant SI topics, but are often found in conjunction with other SI practices.

The few knowledge and human resource-related studies demonstrate the effects these factors have on efficient resource use. Information on local environmental conditions, seasonal variability and crop requirements allow for optimisation of the timing and location of resource inputs (Gadanakis *et al.*, 2015). Labour productivity is addressed with respect to the optimal planning of available labour input (Wang *et al.*, 2016), synergy effects through diversification (Bunting *et al.*, 2015) and the adjustment of farm and field sizes accordingly (Bos *et al.*, 2013; Rusinamhodzi *et al.*, 2016).

Land Use Allocation (FoA III)

Research which focusses on targeted and planned land use allocation based on regional needs and capacities in order to enhance landscape functioning and (agro-) biodiversity is included in FoA III ‘Land Use Allocation’ (N=66; 10%). It includes approaches which aim at improving the joint provision of various environmental services in the same landscape and/or to produce the same amount of food and biomass on less land or in a different organisation of land.

A prominent part of the literature in this FoA concerns the elaborations about landscape design and its declination in the land sharing and land sparing SI approaches (Shackelford *et al.*, 2015; Dauber and Miyake, 2016). The scarcity of land available for conversion to agriculture in order to feed the increasing population, combined with the parallel need of biodiversity conservation, requires the holistic integration of productive and natural spaces at the landscape level (Fischer *et al.*, 2014) and the identification of possible innovative land use practices (Grau *et al.*, 2013). Many examples of these two SI approaches are related to the coexistence on a specific landscape of agricultural production, such as livestock and pastures (Mastrangelo and Gavin, 2012) or coffee plantations (Gordon *et al.*, 2007), and natural elements indicating a good level of biodiversity, such as native vegetation and birds. Mixed crop-livestock systems on the landscape scale are also included in this FoA. They increase the diversity within the agricultural systems and allow the improved regulation and maintenance of environmental services through a diversified landscape mosaic (Lemaire *et al.*, 2014).

In the literature, most of the studies (N=32; 49%) are focussed on planning and zoning. In some cases, they are concerned with improving coordination between input and output marketing systems (Reardon *et al.*, 1997), whereas in other cases they act through the implementation of agro-environmental measures assuring the maintenance of specific societally supported agro-ecosystems (Hecht *et al.*, 2016).

Regional Integration (FoA IV)

Focussing on approaches of structural improvements at regional level, the FoA ‘Regional Integration’ (N=166, 26%) encompasses manifold topics of knowledge exchange and innovation diffusion, functioning of institutions, governance mechanisms and local networks. Many contributions highlight the important role of cooperation and exchange between different actors at the regional level for different purposes, such as common resource use, value chains and marketing strategies. This also includes non-farming actors, such as policy and decision-makers, the local community and economy at large.

Multi-level and multi-stakeholder networks are found to enable common resource use, redistribute inputs and close nutrient loops. Examples include regulatory schemes for irrigation management at the regional level (Pretty *et al.*, 2011). This FoA also concerns the integration of actors in regional marketing activities. For instance, certification schemes establish a common regulatory framework for sustainable farming practices, improve the connection between producers and consumers and build consumer confidence (Buckwell *et al.*, 2014). In addition, institutional changes such as taxation, land tenure policies or access to credits, but also improved forms of leadership and governance are highlighted as triggering SI (Southern *et al.*, 2011; Bird, 2014).

With 40% of contributions to this field (N=66) the most frequently addressed topic, however, is regarding the question of knowledge and innovation diffusion (Shiferaw and Holden, 1998; Buckwell *et al.*, 2014; Campbell *et al.*, 2014). Regional networks, which open channels of communication, awareness raising and trust among different actors (Bebbington, 1997) facilitate the diffusion of knowledge and novel practices. Other papers explicitly emphasise the role of extension services (Baulcombe *et al.*, 2009), but also the effectiveness of farmer-to-farmer learning (Pretty *et al.*, 2011).

2.4.3 Comparing fields of action for SI

The farm level is the dominant spatial scale on which SI practices are investigated. Addressing SI at a superordinate landscape level of regional land-use planning or steering societal interactions and regional integration is underrepresented in comparison (Figure 2.5a). A major share of the literature (47%) takes a specialised perspective on SI as authors cover a particular field of action and then tend to focus on a single selected practice (Figure 2.5b). More integrated perspectives rarely go beyond coupling more than two fields of action (13%). 21% of the papers do not consider practices of SI in abstracts or conclusions.

Altogether, the literature shows that a broad scope of the application of SI practices exists across and within FoA. This conceptual approach amalgamates and structures SI practices and thus the SI literature as facets and aspects of a multidimensional notion. The results can be summarised as the second *proposition (2.2)*, that taking into account the differences in spatial scale and activity scope of SI allows the integration of the diverse SI practices within a common conceptual framework.

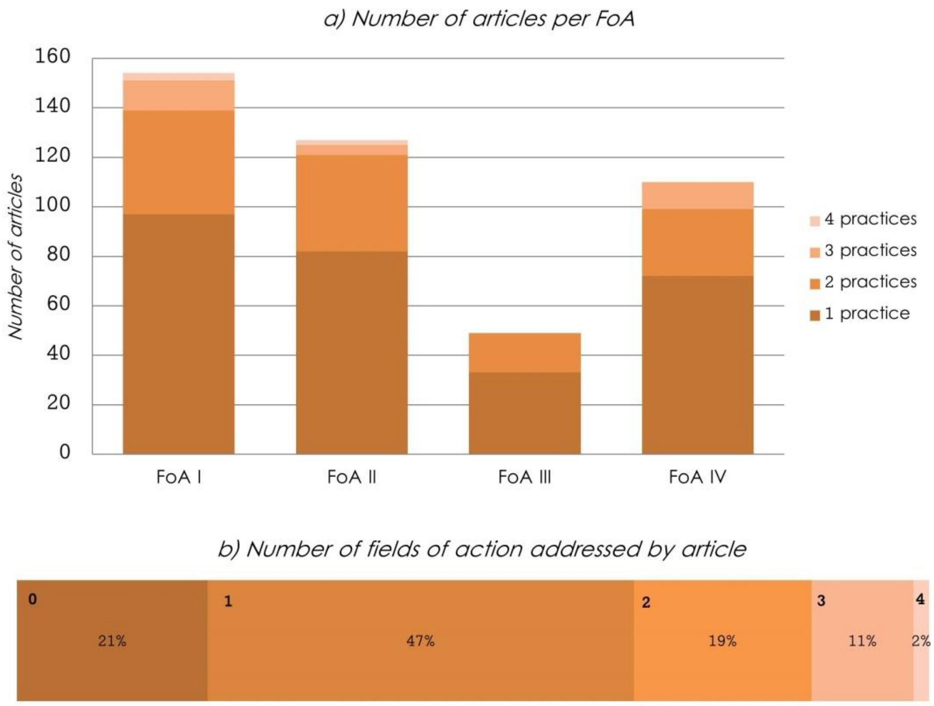


Figure 2.5 Coverage of the FoA in the scientific literature (N=349).
Source: Own representation.

2.5 Application of the conceptual framework in regional case studies

To particularise the generic framework to specific regional settings, relevant SI practices are identified with the support of regional stakeholders involved in decisions on land use. The four case study regions are characterized by different land use practices, levels of intensity, as well as ongoing change processes and future challenges (Figure 2.6). Together, the case studies represent major agricultural land use types in Europe and cover a variety of situations in terms of urbanisation and environmental problems. The generic conceptual framework should be applicable to a wide range of regional settings.

The SI trends in the case studies reflect the diversity of the different land-use systems and challenges. Nonetheless, in each region the SI agenda addresses all four FoA. Figure 2.7 depicts the results of stakeholders' assessments on the SI approaches currently applied and which they consider additionally relevant for the future. For the current and future situation, the frequencies with which any given SI approach was suggested as a solution are displayed. To account for different sizes of stakeholder groups and total suggested solutions, regional frequencies are weighted up or down to represent each region equally.

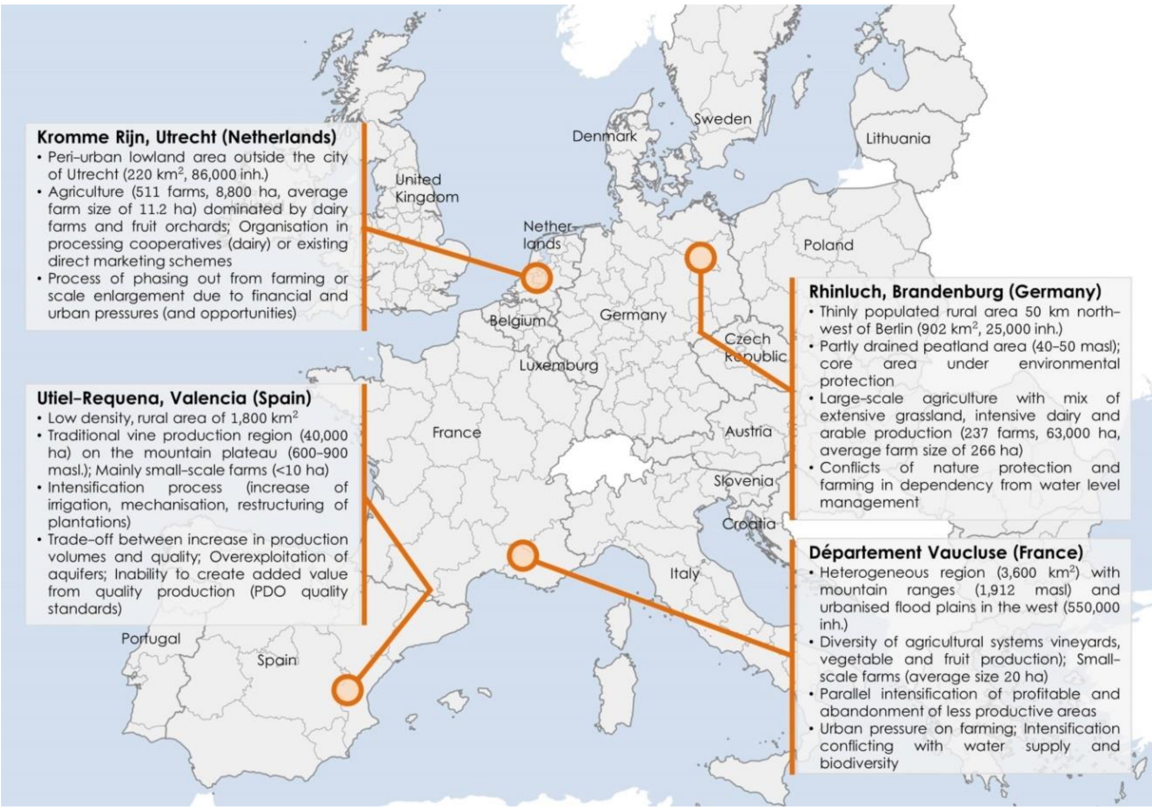


Figure 2.6 Description of case study regions.
Source: Own representation.

Focussing on the current situation, on the farm level in accordance with the literature adapted cropping practices (FoA I) are dominant. Further, efficiency gains especially in terms of pesticides, water, and residue use but also labour productivity mainly related to the restructuring of the farm income base play a role. Specificity becomes apparent in how the respective regions elaborate the FoA. Adapted cropping in the form of integrated farming systems is practiced in Vaucluse with horticulture and fruit orchards. New crops are introduced according to regional needs such as legumes delivering proteins for livestock in Rhinluch or almond trees which are less water dependent than vine in Utiel-Requena. Adapted husbandry is applied in the German case study via rotational grazing systems and adapted stocking densities. FoA II, ‘Resource Use Efficiency’, dominates in Vaucluse and Kromme Rijn. Specifically biological pest control and integrated pest management in the permanent crops typical for both regions are important. In Kromme Rijn, additionally the use of manure to close nutrient cycles is prominent, but mainly triggered by agricultural policy. Political support also incentivized actions to save water resources in Utiel-Requena, e.g. through underground drip irrigation. In the field of ‘Land Use Allocation’ (FoA III), the peak in land sharing practices mainly relates to the uptake of agri-environmental schemes promoting buffer strips, field margins and landscape elements. Land sparing is addressed through voluntary land allocation schemes to protect biodiversity which are taken up in the German and the Dutch cases. Regarding ‘Regional Integration’ (FoA IV), in the Vaucluse region short value chains are widespread and strictly related to its urbanised land structure. Spanish farms also engage in FoA IV via the exchange of manure with other farms and collective action of networks of neighbouring farmers such as fighting the grape moth.

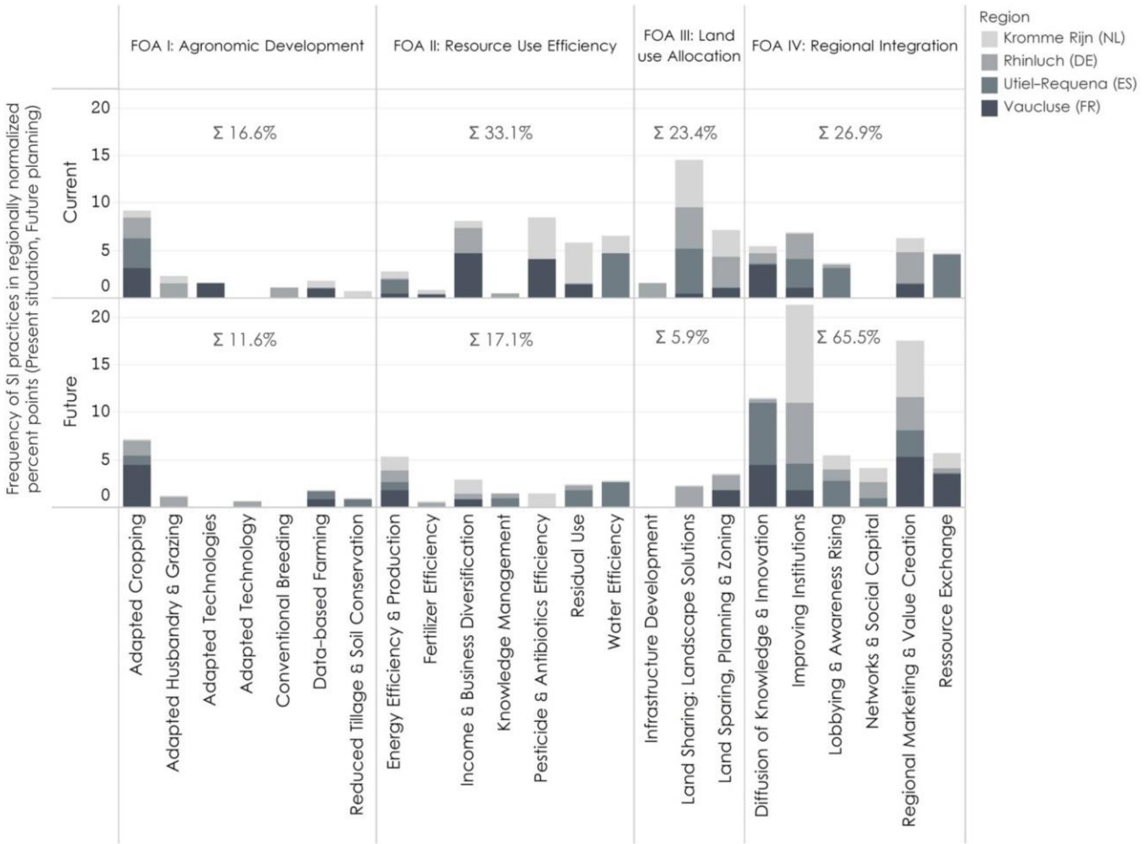


Figure 2.7 Current and future SI practise in four European case studies determined in a participatory stakeholder process.

Note: Bars display the frequencies of proposing a SI approach in the current and future situation. Regional frequencies are weighted to represent regional results equally by normalizing the absolute sum of all frequencies in a situation to 100 adjusted in such a way that each region makes up for 25 points in total in the frequency index. Approaches not mentioned by stakeholders: Biotechnology and Genetic Engineering (FoA I); Adapted Livestock Fodder; Soil Management Systems; General Resource Efficiency (FoA II).

Source: Own representation based on focus group results.

Regarding currently missing SI approaches and future need for action, stakeholders in all regions strongly emphasize practices on the landscape and regional level in the field of 'Regional Integration' (FoA IV). Stakeholders suggest that future improvements should be prompted through collective action and public policy. Dutch stakeholders strongly demand improved institutions to standardise regulations within the EU and the increased sale of local products via retail chains, e.g. using common labels as a regional marketing strategy. Both practices aim to reduce external competition and thereby the financial pressure on local farmers. In terms of regional marketing and value creation, French and German stakeholders also see a need for improvements in the local agro-food chain underlining the importance of collective strategies among farmers for sales and promotion.

In Vaucluse, the need for knowledge diffusion, namely through farmer education and agricultural experimentation is additionally highlighted. This view is shared by their Spanish counterparts who describe efficient water use and fertilization management as site-specific and knowledge-intensive. To be carried out appropriately, technical assistance and awareness raising among public (i.e. agricultural administration) as well as private agents (i.e. cooperatives) are suggested. Resource exchange in terms of administering common use is required in the area of regional water management. In Vaucluse, this addresses the irrigation network and in Rhinluch the drainage system. Networks and social capital are mainly raised as supporting requirements for implementing other practices. Stakeholders in Rhinluch identify tourism as an area in which farmers and other local stakeholders must cooperate to market the region as a recreational area and natural habitat. PDO labelling in Utiel-Requena has similar challenges to be addressed. It requires coordinated action, trust in the enforcement of common agreements, and a leading institution to increase grape quality, and thus revenues, by reducing production volumes.

The conceptual framework of the four FoA encouraged stakeholders to identify and discuss key challenges. Regional discussions yielded holistic SI agendas. The results from the case study regions with their diverse regional background situations lead us to our third *proposition (2.3)*, that the specific context determines the relevance and design of regional SI solutions. There is 'no one size fits all'. Knowledge of regional farmers and stakeholders is required to explore suitable SI practices and their interaction with the local ecosystem.

2.6 Discussing and connecting perspectives on SI

2.6.1 Heterogeneity in the SI literature

As the consolidated development of the SI literature body – after a period of sharp increase – included in our database suggests, now is a suitable moment to retrospectively develop a comprehensive picture of the SI research through a systematic, interdisciplinary screening. The geographical pattern reflects ongoing political and societal discourses, starting from investigations of extensive systems mainly in the Global South, and moving to highly intensified systems of the Global North. Whereas in Europe SI attained increasing prominence from policy-making (Buckwell *et al.*, 2014) as a reaction to increased environmental pressures (Baulcombe *et al.*, 2009) and a long tradition of common agricultural policy-making, the experience of the deregulation of the agricultural sector in New Zealand has led the way to intensification and a departure from ecological sustainability (MacLeod and Moller, 2006). In the US some political documents even eschew the term 'sustainable' due to the term's negative connotations for some interest groups (Godfray and Garnett, 2014). This might explain why in both world regions, SI has been barely addressed as a scientific topic.

Results also point to a notable underrepresentation of SI in economics and social sciences compared to agricultural, biological and environmental sciences (cf. Fig. 2.2b). This is certainly partly due to differences in the terminology used for the same or similar phenomena, such as eco-efficiency (Picazo-Tadeo *et al.*, 2011; Areal *et al.*, 2012) or joint production of marketed agricultural and non-marketed environmental goods (Wossink and Swinton, 2007). The use of the search term 'sustainable intensification' resulted in a narrow selection of articles, as we wanted to focus on authors who deliberately discuss their work under this terminology, being also aware that other parts of the research – which take place outside this narrow use of the notion – are neglected in the review.

Reluctance to use the term SI may be rooted in the partially normatively and ideologically loaded discourse surrounding it. Critics frame SI as an oxymoron (Struik *et al.*, 2014; Mahon *et al.*, 2017), a neo-productivist approach (Levidow, 2015) or a way to disguise the maintenance of the status-quo in agricultural production (McDonagh, 2014), whereas proponents speak of a new paradigm in environmental policy (Franks, 2014). Voices that call for midway strategies (Jordan and Davis, 2015) or for framing SI as one part of a multidimensional strategy for food security (Godfray and Garnett, 2014) might be overlooked. Disconnection in the SI literature is also found in the citation pattern, namely between the initial and the recent SI literature. It might be explained by a strong focus to very specific topics covered in the first phase of SI research e.g. on social capital as a key driver for local adoption of SI practices (Bebbington, 1997) or suggesting a holistic SI agenda but for a very specific system (Balasubramanian *et al.*, 2007). Afterwards the discussion substantially broadened (Wezel *et al.*, 2015) which might explain why authors have very different perceptions on SI. Since overarching papers for the internal SI literature are missing, this paper's contribution to advance the topic is to identify and describe unifying elements and to tie up loose ends (proposition 2.1).

2.6.2 Conceptual framework of SI

The systematisation of SI in the proposed conceptual framework pursues a bottom-up approach with a strong emphasis on the actual SI praxis (proposition 2.2). In this way, we diverge from the theoretical delineations of partly competing ideas such as sustainable intensification, ecological intensification, climate-smart agriculture or agroecology (e.g. as done in Campbell *et al.*, 2014; Wezel *et al.*, 2015). A large portfolio of SI practices exists because SI does not privilege any type of implementation (Suhardiman *et al.*, 2016). Moreover, the contexts in which SI practices are applied differ widely, ranging from the intensification of underperforming agricultural systems (Mueller *et al.*, 2012) to the redesign of intensive systems in order to decrease their environmental pressure (Robinson *et al.*, 2015). In contrast to terminology influencing the acceptance of concepts (Godfray and Garnett, 2014), starting from implementation is relatively neutral.

The framework integrates a literature that has shown to be relatively specialised. Thus it can guide the selection of suitable SI practices when designing local solutions (Buckwell *et al.*, 2014; Wittman *et al.*, 2016). A closer look at the four described FoA shows that many practices are already commonly implemented by farmers and investigated in research. Adapted cropping practices such as legumes and intercropping, for instance, have been discussed as means for sustainable agriculture for many years. Institutional progress in general is seen as a key issue for agricultural and rural development (Dorward *et al.*, 2004).

Considering the framework from a holistic perspective, the novelty of SI rather lies in the possibilities of strategically coupling different fields of action, approaches and practices. The key challenge here is the identification and adoption of suitable SI practices by relevant actors. The adoption of new SI practices on the farm following evidence from technology adoption literature is a long and dynamic process depending on risk preferences, neighbourhood effects, peer-group learning and past innovation experiences (cf. e.g., Sauer and Zilberman, 2012). Drivers for SI adoption have farm-type dependent effects (Firbank *et al.*, 2013). Coordinated efforts, collective action and communication are required as soon as multiple actors are engaged and practices must be applied on larger scales than the single farm (Ostrom, 2010). Adoption of SI practices will be analysed in detail in Chapter 3 of this dissertation.

Several reasons add to the fact that those SI practices involving decisions of multiple actors, namely in the fields of 'Land Use Allocation' (FoA III) and 'Regional Integration' (FoA IV), are relatively underrepresented in the literature. The complexity of governance and planning mechanisms do not lend themselves to easy analysis. They are not easily quantifiable and they take more time and coordination to study especially if societal actors are included in the research (Mauser *et al.*, 2013). Thus, this kind of studies might be less commonly carried out. However, these authors might also be more reluctant to connect their studies to the disputed SI literature (Godfray and Garnett, 2014).

2.6.3 Regional applicability and particularisation

SI practices depend on regional settings, historical developments and current land use practices and, thus, necessarily have distinct shapes in different places and agricultural systems (Barnes and Poole, 2012; Buckwell *et al.*, 2014). Local solutions depend on both environmental and socio-economic conditions (Scherer *et al.*, 2018). In all four cases in which the framework was applied our results revealed holistic solutions covering all FoA depending on the problem context and local knowledge (proposition 2.3).

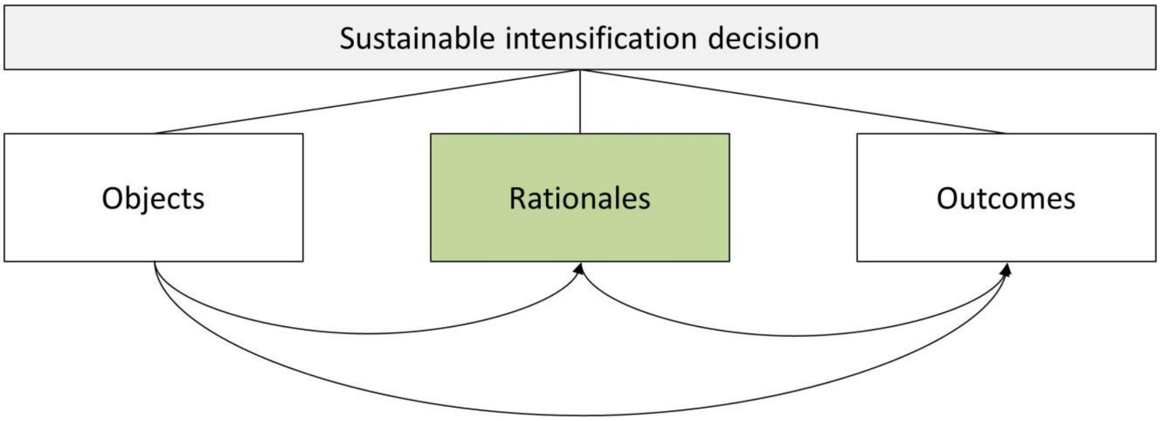
The communication process between regional actors played a crucial role. It revealed priorities, rationales of thought and action on the part of land users, and shed light on conflicts. Prior research has shown that, if individuals can have discussions on an informed basis, with knowledge of who else is affected by the same problem and learn about each other's positions in a neutral atmosphere, reciprocity and trust-building can be enabled and room for common actions and solutions discovered (Ostrom, 2010). Regional knowledge and experience have been identified early (Bebbington, 1997) and are about to be rediscovered (Wittman *et al.*, 2016; Garibaldi *et al.*, 2017) as crucial for progress towards SI. An important point that may help to resolve criticism of SI is that regional acceptance and compromise is needed in order to implement SI practices and thus a generic framework of SI can be value-neutral and must not exclude certain practices in advance.

In its mixed-method approach, this chapter entails a methodological advancement. It integrates a systematic literature review with a qualitative case study approach including the knowledge and expertise of regional stakeholders. Thus a structured, generic procedure is matched with particularised, problem-specific results. The scientific and practical knowledge can be linked and compared. For SI covering a broad range of topics and disciplines, this is a promising approach to synthesize understanding, as case studies are especially useful when the phenomenon under investigation is complex and regional particularisation is required (Lokke and Sorensen, 2014). In-depth case studies and participatory processes are needed to understand SI from a system perspective and to pursue reality checks (Wittman *et al.*, 2016). Unlike the scientific literature, practitioners see a clear need for future action on the landscape scale, namely in FoA IV 'Regional Integration'. Important issues raised are exchange, networks, trust, mutual learning and coordinated action. Thus a gap between science and practice seems to exist that needs to be addressed.

2.7 Conclusions

With this systematic literature review in this chapter, we have developed a conceptual framework of SI that enables action-based access to a heterogeneous field of research. In a structured way, the framework defines the scope of SI, contributes to a holistic understanding and offers a mode to unify diverging perspectives. A broad portfolio of SI practices and detailed assessments of single SI approaches exist. However, little effort is devoted to study SI as an objective requiring integrated practices, coupling the farm and landscape scales and different fields of action. This also requires addressing decision-making structures of various agents on different scales. In order to pursue a future-oriented SI research agenda, interdisciplinary cooperation is needed to address SI from a holistic perspective. The focus should be on the implementation of approaches paying attention to the behavioural rationales of farmers and land users. In many contexts, coordinated and collective decision-making will be required which is facilitated by local discussion and coordination. The proposed framework has proved able to support and guide regional discussions, integrate local knowledge on fruitful SI practices and allow different stakeholders to communicate on solutions for region-specific problems involving different views and demands. In doing so, practitioners identified the need for regional coordination, integrated solutions and common action; now research has to follow suit.

3 On the relevance of portfolio effects in adopting sustainable farming practices



This chapter is based on the following article:

Weltin, M., Zasada, I., Hüttel S. (2020). On the relevance of portfolio effects in adopting sustainable farming practices. Manuscript submitted for publication.

3.1 Introduction

Currently, many commonly used agricultural practises contribute to environmental damage such as biodiversity loss, water degradation, and greenhouse gas emissions. Suggestions for considerably reducing these adverse effects include strongly increasing the adoption of sustainable practices (Thomas *et al.*, 2019). Consequently, the concept of sustainable intensification (SI) unifies such sustainable practice measures, which enable increasing or at least maintaining crop yields with reduced environmental harm and without transgressing land and water boundaries (Pretty, 2018). Large-scale adoption of SI can help to establish environmentally and socially sustainable but secure food production systems (Foley *et al.*, 2011).

At the farm scale, SI measures embrace regionally adjusted resource-saving production systems or techniques, such as inter and mixed cropping, reduced tillage, precision farming with site-specific field management, and integrated pest management (Petersen and Snapp, 2015; Dicks *et al.*, 2019). At the regional and landscape scale, propositions for SI include land sharing or sparing arrangements, short food supply chains, or the exchange of knowledge and other resources among farms and along the supply chain (Buckwell *et al.*, 2014; Shackelford *et al.*, 2015). The measures share an aim to curtail input use, actively interact with the local environment, and reduce negative externalities through improved efficiency. Smart mixes applied at both scales may even generate positive environmental externalities (Qiu *et al.*, 2015).

Despite these advantages, adoption rates are low and research findings on the benefits of SI seem to be rarely transferred to commercial farms, which may impede possible sustainability improvements (Manning *et al.*, 2019). Approximately 30% of farms worldwide are estimated to use agronomic SI measures, albeit with considerable variation across measures and regions (Pretty, 2018; Dicks *et al.*, 2019). Discussed barriers include limited available farm resources, with time and labour being discussed in particular regarding conservation practices (Meraner *et al.*, 2015; Lemken *et al.*, 2017). Furthermore, high investment and learning costs may hamper adoption, e.g. reported for precision farming (Rogers *et al.*, 2016; Barnes *et al.*, 2019), as do uncertainly perceived cost savings or economic benefits (e.g., D'Antoni *et al.*, 2012), and perceived incompatibility of measures with current farm technology (e.g., Reimer *et al.*, 2012). Additional adoption barriers are potentially rooted in unclear knowledge of the environmental benefits of conservation measures (Greiner, 2015), insufficient previous innovation experience (Sauer and Zilberman, 2012), a lack of business skills e.g. for direct marketing (Park *et al.*, 2014), or missing exchange opportunities with peers in spatial proximity (e.g., Läpple *et al.*, 2017). Despite the large body of literature, a clear pattern of fostering and inhibiting factors for the adoption decision of SI practices seems not to exist, with only a few studies making the necessary link to geographical and practice-specific contexts explicit (cf. Knowler and Bradshaw, 2007; Foguesatto and Dessimon Machado, 2019).

Adopting SI may bring about new farming type, as well as a paradigm shift in land management (Lindblom *et al.*, 2017). At the time of the adoption decision, effects on the farming process as a whole can be difficult to assess, resulting in a complex decision process (Pathak *et al.*, 2019). Behavioural models seem suitable for investigating adoption behaviour, though are represented by a rather small but growing body of literature (Dessart *et al.*, 2019). Accordingly, social norms (e.g., Kuhfuss *et al.*, 2016) and knowledge generation (e.g., Smith *et al.*, 2018) are noted as being relevant to farmers' pro-environmental behaviour. Furthermore, environmental attitudes have been shown as relevant antecedents for the adoption of sustainable farming practises (e.g., Greiner *et al.*, 2009). Bonke and Musshoff (2019) highlight the relevance of perceived environmental benefits for the attitude as a predictor of the adoption intention of mixed cropping, as Werner *et al.* (2017) do concerning cover crops. Both studies, however, neglect belief-formation as proposed by the more recent Reasoned Action Approach[3] (cf. Fishbein and Ajzen, 2011). Furthermore, the core idea of SI is that economic and ecologic sustainability benefits are best achieved by smart mixes of measures (Firbank *et al.*, 2013). Farmers' intended SI portfolios may depend on their experience and perceptions of economic and environmental outcomes of implemented measures (e.g., Reimer *et al.*, 2012), making a gradual adoption process likely (cf. Van Hulst and Posthumus, 2016; Lemken *et al.*, 2017).

[3] According to RAA, individual behaviour rests on behavioural intentions, which can be represented by an individual's attitude towards the behaviour, perceived norms, determined by the influence of other individuals or society as whole, and perceived behavioural control which is represented by the possibilities of an individual on influencing the behaviour (Fishbein and Ajzen, 2011). Each of these three dimensions is rooted in respective beliefs.

Against this backdrop, questions arise such as whether there exist regional key SI measures that can trigger uptake or intention concerning the future adoption of other measures, and questions that concern the role of related experiences and perceived benefits. According to our knowledge, however, behavioural foundations have not yet been suitably adjusted for investigating gradual SI adoption behaviour. Likewise, SI contextual issues, such as societal pressure for increased sustainability, and positive or reduced negative externalities of SI farming, are yet to be integrated into a unified theoretical base (Schlüter *et al.*, 2017).

In this chapter, we aim to close this gap by empirically exploring the interrelation of current use of SI measures and intentions to broaden the adoption of SI practices. We explore whether current use and intentions are linked through experience and perceived benefits using a cross-sectional farm survey data set covering the northern German Plain. The given data set allows us to rely on decisions on a regionally adjusted set of SI measures. Using qualitative data collected from focus group discussions, we prioritise regionally contextualised SI measures to investigate in the two-stage empirical analysis of this chapter. First, we explore existing farm portfolios of SI measures and determine how the use of specific SI measures raises the likelihood of observing the co-use of other measures that are complementary by means of a multivariate probit model (cf. Kassie *et al.*, 2015a). Second, we analyse stated intentions regarding the prospective use of additional measures using an explorative partial least squares path model (cf. Reinartz *et al.*, 2009). In the model, we explicitly acknowledge the role farmers' perceptions of economic and environmental outcomes of complementary SI measures, as identified in the first stage, play regarding their intentions to broaden SI portfolios. With the analysis in this chapter, we provide evidence for ***research question 2*** of this dissertation: *Which factors influence farmers' choices of sustainable intensification measures and are these choices interrelated?* While defining the investigated regional portfolio of SI measures based on qualitative data, we draw on the results of Chapter 2 and further contribute to answer ***research question 1***: *Which measures are subsumed under the sustainable intensification concept and how can regionally adjusted portfolios of sustainable intensification measures be identified?*

Our results indicate a complementary relationship in using agronomic, precision farming, landscape, and regional marketing related SI measures. Furthermore, perceived economic and ecological benefits are found relevant for portfolio broadening. The presented mixed-methods approach is required when taking regional specificity of SI into account. Together with the modelling paths found, these results can serve as a base for developing integrated modelling approaches by contextualising behavioural models. Such enhanced theoretical bases offer a causal interpretation of adoption decision determinants, and are a precondition for the development of intervention schemes for achieving greater farming sustainability (cf. Yoder *et al.*, 2019).

We continue by detailing the idea of how smart mixes of SI measures may ease exploiting potential of ecological and economic benefits and how portfolio decisions come into play (Section 3.2), subsequently presenting the study data and our explorative empirical approach (Section 3). We present and discuss the results (sections 3.4 and 3.5), and conclude (Section 3.6).

3.2 SI adoption as a key for more sustainable farming

SI measures represent a portfolio of agronomic approaches, technological innovations, and business models targeted at raising economic, environmental, and even social sustainability. Among the agricultural systems of the global North, ecological improvements and input efficiency are prioritised (Godfray and Garnett, 2014). Precision farming, for instance, offers savings on fuel and fertilizer (Jensen *et al.*, 2012), thereby reducing greenhouse gas emissions and risks of environmental harm such as nutrient leaching and pesticides' active substance contamination of soils (Wolfert *et al.*, 2017). Similarly, site-specific input offers the possibility of better integrating nature conservation into crop management, and thereby make a relevant contribution to biodiversity (Schieffer and Dillon, 2015). Flower and buffer strips are examples of such integrated semi-natural habitats and may, if adopted across farms, preserve biodiversity at the landscape scale (Green *et al.*, 2005). Extensive land management is particularly relevant regarding peatland areas serving as carbon sinks and natural habitats of breeding birds (TEEB, 2015). Almost 40% of the surveyed farmers in our sample from the northern German Plain partially operate on peatland areas; hence the sample is interesting from an environmental management perspective. Extensive management may be incentivised and rewarded through higher trust and consumers' willingness to pay, for instance through direct marketing schemes (Levidow, 2015) or certificates (Günther *et al.*, 2018).

Smart mixes of SI measures, such as supply chain management, performance monitoring, resource-saving technologies, and the use of marginal land for buffers or hedgerows, can raise farms' performance in environmentally balanced food production (Firbank *et al.*, 2013). However, regional context determines the portfolio of relevant SI practises (Dicks *et al.*, 2019) and the effectiveness of specific combinations of SI measures (Pretty and Bharucha, 2014; Giller *et al.*, 2015), an issue often neglected when analysing adoption decisions. In the adoption process farmers' corresponding selection can depend on locally differing social norms (Mills *et al.*, 2017) and viewpoints (Franks, 2014). Here, mixed-method approaches connecting qualitative and quantitative evidence have been proposed to analyse the context-specific adoption process (Burton, 2004). To our knowledge, such approaches have rarely been applied in the context of sustainable farming practises (Leonhardt *et al.*, 2019 provide an exception). In our approach, we follow this idea, using qualitative data to identify locally relevant SI measures, and quantitative data to explore adoption patterns.

Adoption of an SI measure affects a farm's prospect of profits through input savings and respective yield expectations, both by the time of the adoption unclear, and adoption may also affect environmental outcomes beyond the farm level (cf. Barnes and Thomson, 2014; Godfray and Garnett, 2014). This makes a respective measure's outcome after adoption difficult to predict, and for an individual potentially difficult to assess or imagine. Such an assessment may be even harder for a portfolio of measures, particularly when adoption affects farm technology and business process (cf. Aubert *et al.*, 2012). A large fraction of adoption studies seem to focus on adoption decisions on single measures, such as conservation practices (e.g., Lemken *et al.*, 2017), new technologies (e.g., Sauer and Zilberman, 2012), or business development (e.g., Hansson and Ferguson, 2011). Thereby better educated farmers are frequently found to be more likely to adopt environmentally sustainable practices (e.g., Raymond and Brown, 2011;

Läpple *et al.*, 2017). Furthermore, farm size and farm specialisation have been reported as relevant for adoption, though with contradictory results (e.g., Uematsu and Mishra, 2011; Tey and Brindal, 2012). The influence of such factors has been shown to depend on the SI practice studied (Knowler and Bradshaw, 2007) and provides insufficient explanation for adoption patterns since multiple and reverse pathways exist, making causal interpretation in the complex adoption process difficult (Burton, 2014; Pathak *et al.*, 2019).

Taking the behavioural perspective, Thomas *et al.* (2019) show that the environmental attitude of farmers denotes an important predictor for the adoption behaviour of sustainable practises. Risk aversion, however, can interfere and inhibit pro-environmental management (Trujillo-Barrera *et al.*, 2016). A growing strand of literature emphasizes the role of information and knowledge generation (e.g., Smith *et al.*, 2018), and farmers' social capital gained through network interactions (Rantamäki-Lahtinen, 2009). Accordingly, the role of social norms for adopting pro-environmental management practises is emphasized (Burton, 2004; Kuhfuss *et al.*, 2016; Le Coent *et al.*, 2018), but also mentioned as being hitherto under-researched (Carroll and Groarke, 2019; Chabe-Ferret *et al.*, 2019; Dessart *et al.*, 2019; Palm-Forster *et al.*, 2019). Bonke and Musshoff (2019) provide a recent exception, and point to positive influences on peer-group opinions for adopting mixed cropping as an agronomic SI measure; they also emphasize the role of expected environmental benefits to form attitudes pertaining to sustainable practices. Reimer *et al.* (2012) highlight the potential role of perceived relative advantages and disadvantages of SI measures. Yeboah *et al.* (2015) emphasize previous experience with similar measures. These perceptions seem particularly relevant when adopting a portfolio of SI measures, an issue that is rarely considered when investigating adoption patterns (cf. Yoder *et al.*, 2019).

Complementary relationships of SI measures for achieving economic and/or ecological effects are likely to play a role in adoption decisions. Wollni *et al.* (2010) show conservation agriculture in Honduras as able to serve a production system that includes multiple SI practices. Farmers may aim to achieve a resilient portfolio of measures that can balance economic and environmental sustainability effects (cf. Pretty and Bharucha, 2014), with Kassie *et al.* (2015a) and Rodríguez-Entrena and Arriaza (2013) find interdependencies of adoption decisions. Most of these studies, however, focus on the global South. To our knowledge, SI portfolio decisions in the global North seem hitherto under-researched, and may suffer from a missing consensus framework for studying adoption behaviour towards sustainable practices (Yoder *et al.*, 2019). Reimer *et al.* (2014) note that relationships among potential explanatory factors for adoption decisions must be better understood to refine theoretical models of adoption behaviour. We aim to help close this research gap by using an existing data set to explore relationships among decisions on the use of SI measures from the regional portfolio. We can make use of information on experienced benefits from adopted SI measures, farmers' sustainability attitudes, and farmers' interactions in social networks. We explore the role played by these factors concerning the future adoption of other SI measures.

3.3 Material and methods

We follow Hansson and Ferguson (2011) in separating the analyses for different aspects of the complex decision-making process, employing this as a pre-step for an integrated modelling approach. First, we prioritise a regionally adjusted portfolio of SI measures based on qualitative data. Subsequently, we differentiate farmers' current use of SI measures of the regional portfolio and intentions to broaden the SI portfolio on the farm into two explorative quantitative modelling stages.

3.3.1 Data

Our analysis is based on existing farm survey data on both the use and consideration to use SI measures. Surveyed farmers (N = 410) indicated their current use or non-use of 17 SI measures, while non-users stated their intentions to use SI measures in the future. The full questionnaire is provided in Appendix B. Data were collected from February to June 2017 and cover the northern German Plain in areas with high shares of peatlands.[4] Farmers in the respective areas of the federal states of Brandenburg, Mecklenburg

[4] The selection criteria were postal code areas with 20% peatland area and 1,000 ha peatland area in total, or 5,000 ha peatland area in total. Overall, 3,000 farmers were contacted. Farmers could respond online or by mail. The response rate was 13.5%. Details on sampling and the questionnaire can be found in Weltin *et al.* (2019).

Western Pomerania, and Saxony-Anhalt were directly addressed by mail and via local farmers' associations, through the latter additionally in Lower Saxony and Schleswig Holstein. We exclude 26 farms with an area below 5 ha from the quantitative analysis because small farms frequently represent behavioural outliers (cf. Raymond and Brown, 2011).

The place-based knowledge and views of stakeholders involved in agricultural land use supports the definition and prioritisation of locally adapted and context-specific SI measures (Franks, 2014; Dicks *et al.*, 2019). Regionally relevant SI measures were discussed within focus groups with stakeholders in the Rhinluch region (Brandenburg) prior to survey data collection. The Rhinluch region is representative of the surveyed area in terms of being characterised by agricultural land use in lowland peatland areas. Stakeholder groups include farmers, representatives of nature protection bodies, and regional administration involved in land and water regulation, all of which were selected via snowball sampling (cf. Reed *et al.*, 2009). The selection of SI measures for the farm survey was guided by the focus group discussions and a systematic literature review; this reduces the risk of understanding bias in the data.[5] We use the available qualitative data to prioritise SI measures for this chapter. We first group similar measures. Subsequently, we use participant responses across all focus groups to build a priority score, adding up how frequently a cluster of measures had been named and selected among the three most important clusters.

3.3.2 Exploring current use of SI

Starting with exploring the current use of SI measures and how farmers' combine these measures, we analyse correlations among the decisions concerning the single SI measures of the regional portfolio. We acknowledge differences between farm and farmers' characteristics to capture the relation between farm type and its most suitable SI portfolio (cf. Franks, 2014; Dicks *et al.*, 2019). Deciding to adopt an SI measure might be conditional on the use of others or may be restricted by the availability of substitutes.

[5] In a workshop in November 2016, 16 participants discussed currently applied and prospectively viable SI measures. This was undertaken using three moderated focus groups based on the conceptual framework of SI presented in Weltin *et al.* (2018b). Each participant could assign a maximum of three points to the SI measures that they considered most important (cf. Weltin *et al.* (2016) for details).

As univariate choice models may lead to biased and inefficient estimates (cf. Khanna, 2001), we use a multivariate probit model following Kassie *et al.* (2015a).

Farmers are assumed to choose a combination of SI measures to maximise utility. The utility from applying a measure $j = 1 \dots M$ of farmer i is latent, and is denoted by variable y_{ij}^*. The system of latent adoption equations is then represented by

$$y_{ij}^* = \boldsymbol{x}'_i \boldsymbol{\beta}_j + \varepsilon_{ij},\ j = 1 \dots M, \tag{3.1}$$

where vector $\boldsymbol{x}_i$ contains observed farm characteristics. Here, we use farming experience and education, as well as the characteristics of their farm business and its scale; this includes farm size and fulltime operation, specialisation and organic status, labour intensity, and external knowledge input through advisory services (cf. Knowler and Bradshaw, 2007; Foguesatto and Dessimon Machado, 2019). We also include for each SI measure the percentage of adopters within the same postal code area, this accounts for possible regional similarities due to learning effects or unobserved spatial features (cf. e.g., Läpple and Kelley, 2015).

Symbol $\boldsymbol{\beta}_j$ denotes the respective vector of coefficients capturing the influence of $\boldsymbol{x}_i$ on the use of SI measure j. Error terms are captured by ε_{ij}, and are assumed to follow a multivariate normal distribution with zero conditional mean and variance-covariance matrix $\boldsymbol{R}$, where variance is normalized to unity, and the off-diagonal elements $\rho_{jk\ (j \neq k)}$ denote pairwise correlation coefficients between the error terms of two choices, with a positive correlation coefficient indicating a complementary relationship between the decisions. Use or non-use of SI measures is observed in the result of the utility maximisation process. We follow the general notation and indicate the adoption of a certain measure with 1 in a binary outcome variable y_{ij}, which is observed once latent utility y_{ij}^* (Equation 3.1) is greater than zero. The model is estimated by simulated maximum likelihood estimation with 100 draws using the *mvprobit* command of Stata14 (Cappellari and Jenkins, 2003).

3.3.3 Exploring intentions to broaden the SI portfolio

Based on the multivariate probit model results on correlated and complementary decisions to use SI measures, we analyse intentions to broaden the current portfolios of SI measures. Therefore, we rely on an explorative partial least squares (PLS) path modelling approach, as PLS is proven to be advantageous for exploratory research on behaviour and decision-making model development (cf. Shmueli, 2010; Hair *et al.*, 2011).

For each SI measure j, intention to adopt is modelled to be influenced by the current use of complementary SI measures, and farmers' perceptions of accompanying economic or environmental outcomes. Attitudes towards sustainability and social interactions are further used. We use the classification of behavioural factors of Dessart *et al.* (2019) in dispositional, social, and cognitive factors to group the available variables. Dispositional factors represent relatively stable beliefs, motivations, or preferences, such as the sustainability attitudes. Social factors represent farmers' interactions in their social networks. Cognitive factors cover farmers' perceptions on the relative advantages of specific practices potentially affected by learning and reasoning.

Multiple variables are available in the dataset to capture dispositional, social, and cognitive factors as latent constructs. The PLS path approach allows for reducing the dimensionality of the data while forming the constructs, and provides the advantage of directly incorporating potential relationships between latent constructs by combining confirmatory factor analysis with least squares regression (Venturini and Mehmetoglu, 2019). Indicators for dispositional factors cover farmers' innovativeness, propensity to take business risks, feelings of responsibility for regional economic development, and feelings of responsibility to produce environmental outcomes that are additional to economic goals. Social factors are represented by farmers' frequency of advice and coordination with other farmers, perceived importance of cooperation, and enrolment in formal networks and associations. We follow Henseler *et al.* (2016) and model dispositional and social factors as reflective constructs.

Indicators of cognitive factors describe if and how SI measures are currently used; the first set of variables indicates the current use or non-use of complementary SI measures, those identified in the multivariate probit model from the first modelling stage. As complementary, we consider each pair of SI measures having positive and statistically significant ($p < 0.10$) correlation coefficients. We rely on a composite construct representing the intensity of currently used measures (cf. Aubert *et al.*, 2012). As a second set of reflectively modelled variables, we include whether or not environmental or economic outcomes of complements have been perceived positively by the farmer. As we build separate models for each SI measure, farmers' intentions to apply additional measures in the future, besides that of j, are also included.

Current non-adopters of the respective SI measure j comprise the sample for each model. While exploratively building the model, we split or merged constructs to increase construct reliability, convergent validity, and discriminant validity. We reduce the indicator sets when model quality criteria increase in value, as suggested by Hair *et al.* (2011). Through bootstrapping with 5,000 replications, we generate p-values for the estimated coefficients. The analysis is performed using *SmartPLS (v3.2.8)* software.

3.4 Results

3.4.1 Selection of SI measures and sample

Based on the priority score aggregating how often SI measures were named and selected important during the focus group discussions (cf. Section 3.3.1), we rank groups of SI measures (Table 3.1).

Table 3.1 SI measures and priority scores according to stakeholder workshop results

SI measure group	Priority score[a]	Associated SI measures in farm survey
Regional marketing *(SI_mark)*	22	direct sale, regional labels
Agronomic SI measures (*SI_agro)*	9	reduced tillage, intercropping, min. 5 crops, integrated pest management, legumes
Pasture grazing (*SI_past)*	9	pasture grazing
Landscape elements *(SI_land)*	8	fallow, flower and buffer strips
Technological SI measures *(SI_tech)*	7	precision farming
Livestock breeding	4	not selected for this chapter
New crop varieties	4	not selected for this chapter
Biogas	4	not selected for this chapter
Exchange in regional networks	3	not selected for this chapter

[a]Number of times mentioned + number of times considered important (N=16 participants).
Source: Own representation.

Regional marketing measures lead the ranking, followed by agronomic measures, pasture grazing, landscape elements, and technological SI measures; the latter three have similar priority score values. For parsimony, only the five highest scoring measure groups are used for further quantitative analysis with their associated SI measures from the farm survey.

Due to missing values, farm survey observations vary between 383 and 358 for farm(er) characteristics (Table 3.2). Sampled farms have an average farm size of about 420 ha.[6] Two thirds of the sample are full-time farmers, one third specialises in arable farming, and a fifth is organic farmers.

Table 3.2 Summary statistics

Variable	Obs.	Mean	Std. Dev.
Land [ha]	383	423.53	650.76
Organic farm [1 = yes, 0 = no]	380	0.20	0.40
Specialised in arable farming [1 = yes, 0 = no]	381	0.32	0.47
Full-time farm [1 = yes, 0 =no]	381	0.64	0.48
Labour intensity [workforce/UAA][a]	358	0.05	0.09
Frequency of using extension services [5 categories][b]	374	2.80	1.25
Highest educational degree [3 categories][c]	372	2.31	0.89
Farming experience [years]	367	27.40	13.38
Attitudes towards economic and environmental sustainability			
Feeling responsible for producing environmental outcomes in addition to economic outcomes [10-point scale][d]	366	7.04	2.63
Risk-taking in business decisions [10-point scale][d]	368	5.97	2.52
Innovativeness [10-point scale][d]	362	5.20	2.82
Regional economic responsibility [10-point scale][d]	363	6.91	3.15
Social interaction			
Frequency of advice from other farmers [5 categories][b]	375	3.15	0.91
Frequency of coordination with other farmers [5 categories][b]	374	2.51	1.13
Value cooperation with farmers [10-point scale][d]	367	6.48	2.48
Value cooperation with other stakeholders [10-point scale][d]	366	5.54	2.80
Involvement in networks [number of memberships]	369	1.14	0.88

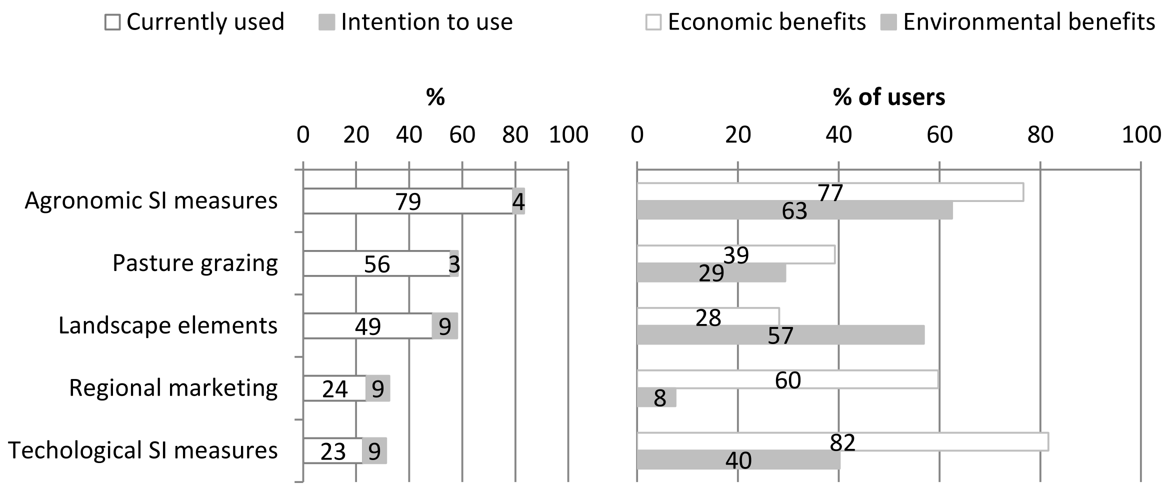
[a] Workforce below or equal to 1 person is summarized as 1.
[b] 1 = never; 2 = sometimes; 3 = occasionally; 4 = often; 5 = very often.
[c] 1 = lower secondary or intermediate education or no degree; 2 = high school degree; 3 = university degree.
[d] Self-assessment questions whereby respondents indicated their degree of agreement on a scale from 1 = fully disagree to 10 = fully agree.
Source: Own representation based on farm survey data.

On average, farmers were found to have 27 years' work experience and engage in one voluntary network, seeking advice from peers more frequently than coordinating their activities with them. Farmers' self-assessments capture their sustainability attitudes. The scores are high for feeling responsible for environmental outcomes in addition to

[6] Of the farms in the sample, 45% are situated in Brandenburg, 37% in Mecklenburg Western Pomerania, and 8% in Saxony-Anhalt. The average German farm size in 2017 was 62 ha. For average farm sizes on federal state level, see Destatis (2017).

economic outcomes. A higher diversity measured in terms of standard deviation exists for the feeling of being economically responsible for the region; for example, as an employer and seeing oneself as among region's first to implement new approaches.

Farmers are considered a user of a group of SI measures if they apply at least one of the SI measures classified in the respective group (Table 3.1). A quarter of sampled farmers use regional marketing and technological SI measures, i.e. precision farming (Figure 3.1a). Other SI measures are used more, with 79% of farmers using agronomic SI measures. Intentions to use additional measures in the future are low, with 9% of farmers intending to apply landscape elements, technological measures, and regional marketing.



a) Percentage of current and potential future users of SI measures (N=410)

b) Percentage of users experiencing economic or environmental benefits from SI measures

Figure 3.1 Farmers' use of SI measures and experienced benefits with the used measures.
Source: Own representation based on farm survey data.

Current users then rated their perceptions as to whether they had experienced economic or environmental benefits from respective SI measures. Economic benefits include increased profits, increased yields, or input savings. Excepting landscape elements, where twice as many users experienced environmental benefits compared with economic benefits, farmers are more likely to rate the SI measures as economically beneficial (Figure 3.1b). The greatest difference is observed for regional marketing, which is perceived as economically beneficial by 60% of users and environmentally beneficial by 8%. Agronomic measures are perceived as the most beneficial in environmental terms (63%), and technological measures the most beneficial in economic terms (82%).

3.4.2 Results: current use of SI measures

Using a likelihood ratio test (χ^2 = 47.08; p = 0.00) we reject the null hypothesis that the correlation coefficients of the error terms of the five equations are jointly equal to zero. Accordingly, the multivariate probit model is preferred over independent univariate choice models. The model results (Table 3.3) indicate the existence of several complementary relationships among the decisions to use SI measures, as indicated by a positive correlation coefficient between the error terms of the adoption equations; however, only one substitutional relationship, between landscape elements and pasture grazing, could be found. Complementary relationships exist between agronomic SI measures and landscape elements $(\rho = 0.64)$, and between agronomic and technological SI measures $(\rho = 0.41)$. Regional marketing has a positive correlation with all SI measures $(\rho > 0.3)$, except pasture grazing.

Table 3.3 Correlation coefficients of the adoption equations' error terms in the estimated MVP model

	SI_agro	SI_past	SI_tech	SI_land	SI_mark
Agronomic SI measures	1				
Pasture grazing	0.16 (0.21)	1			
Technological SI measures	0.41 (0.02)	0.09 (0.45)	1		
Landscape elements	0.64 (0.00)	-0.22 (0.03)	0.20 (0.09)	1	
Regional marketing	0.35 (0.01)	0.08 (0.45)	0.33 (0.01)	0.32 (0.00)	1

Note: p-values in parentheses, N = 330, 100 draws, log-likelihood = -705.58, Wald test $\chi^2(45)$ = 398.60 (p = 0.00).
Source: Own representation based on farm survey data.

For brevity, the full output of the model with coefficient estimates showing the relation of farm and farmer characteristics to decision-making, is presented in Appendix C (Table C.1). Farm size is positively associated with agronomic and technological SI measures, as well as landscape elements. Increasing frequency of using external advisory services raises the likelihood for precision farming and lowers the likelihood for pasture grazing. Organic farms are more likely to engage in regional marketing than conventional farms, but are less likely to use to use precision farming. Specialisation in arable farming is negatively related to pasture grazing, but positively related to agronomic SI measures and landscape elements. A high share of adopters in the same postal code area seems to motivate uptake of all SI measures. Regarding farmers' characteristics, education is positively associated with uptake of agronomic measures, but negatively associated with pasture grazing. Younger farmers are more likely to use technological measures. More work experience raises the likelihood to apply pasture grazing or regional marketing.

3.4.3 Results: intention to broaden the portfolio of SI measures

When exploring intentions to prospectively broaden the portfolio of SI measures, we focus on technological SI measures, landscape elements, and regional marketing to ensure sufficiently large samples of potential users.[7] Thus we estimate three path models. We evaluate the quality of the estimated path models following Hair *et al.* (2011) to determine the final model structure. In all three models, separate constructs of dispositional factors for economic and environmental aspects of sustainability attitudes yield composite reliability scores above the 0.7 threshold, and have an average variance extracted of at least 0.5.[8] For the same reasons, social factors are represented by two distinct constructs: one for values farmers attribute to cooperation, the other for frequency of advice and coordination with peers (cf. Table C.2 of Appendix C). To assess discriminant validity of the constructs we use the heterotrait-monotrait ratio (HTMT) developed by Henseler *et al.* (2015). Excepting that the score for social interaction values and economic sustainability attitude is slightly above the 0.9 threshold, the models fulfil discriminant validity (cf. Tables C.3–C.5 of Appendix C). For cognitive factors, we merge experienced economic and environmental benefits into one construct, as they show problematically high HTMT scores when separated. A moderator effect of the experienced benefits reinforcing the direct effect of complementary measures was tested, but this was excluded from the final model structure. Reasons were discriminant validity and multicollinearity indicated by a variance inflation factor larger than 5.

Table 3.4 shows the indicator loadings and weights for each construct; sets of indicators assigned to the constructs differ slightly across the three models. To preserve the

[7] For each of the three SI measure groups, the share of farmers considering future adoption is 9% (Figure 1a).

[8] The former indicates that the amount of random error in the reflective constructs is sufficiently low. The latter demonstrates convergent validity.

conceptual meaning of formative constructs, indicators should only be excluded when regression weights are very low (Hair *et al.*, 2011). For the construct of using complementary SI measures, we thus exclude indicators with regression weights below 0.1. The reflective experienced benefits construct represents whether or not those economic and environmental outcomes with complementary measures, those included in the current use construct, were perceived positively. The indicator for the ecological benefit in the model for technological SI measures is excluded (non-significant loading below 0.4). We exclude two indicators for social interaction in the regional marketing model to achieve the satisfactory model quality (composite reliability > 0.7 and AVE > 0.5). Indicator loadings of all reflective constructs are statistically significant (p < 0.10).

Table 3.4 Indicator loadings for the constructs in the PLS-SEM models

Construct	**Indicator**	**SI_tech**	**SI_land**	**SI_mark**
Environmental sustainability attitude	Feeling responsible for producing environmental in addition to economic outcomes	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)
Economic sustainability attitude	Risk	0.69 (0.00)	0.72 (0.00)	0.76 (0.00)
	Innovativeness	0.82 (0.00)	0.86 (0.00)	0.74 (0.00)
	Regional economic responsibility	0.84 (0.00)	0.72 (0.00)	0.88 (0.00)
Social interaction activities	Freq. advice other farmers	0.91 (0.00)	0.89 (0.00)	1.00 (0.00)
	Freq. coordination other farmers	0.78 (0.00)	0.82 (0.00)	
Social interaction values	Values cooperation farmers	0.71 (0.00)	0.73 (0.03)	0.77 (0.08)
	Values cooperation others	0.72 (0.00)	0.80 (0.00)	
	Involvement in networks	0.72 (0.00)	0.77 (0.00)	0.77 (0.00)
Use of complements[1]	Use agronomic SI	0.97 (0.00)	0.41 (0.09)	
	Use technological SI	n.a.	0.85 (0.00)	0.72 (0.00)
	Use landscape elements		n.a.	0.49 (0.06)
	Use regional marketing	0.12 (0.78)		n.a
Experienced benefits	Econ. benefit agronomic SI	0.82 (0.00)	0.69 (0.00)	
	Econ. benefit technological SI		0.78 (0.00)	0.83 (0.00)
	Econ. benefit landscape elements			0.43 (0.02)
	Econ. benefit regional marketing	0.45 (0.02)		
	Ecol. benefit agronomic SI	0.86 (0.00)	0.65 (0.00)	
	Ecol. benefit technological SI		0.68 (0.00)	0.76 (0.00)
	Ecol. benefit landscape elements			0.73 (0.00)
	Ecol. benefit regional marketing			
Other future plans	Number of other SI intentions	1.00 (0.00)	1.00 (0.00)	1.00 (0.00)

Note: p-values in parentheses. n.a.= not applicable.
[1] Formative construct: regression weights are presented instead of loadings.
Source: Own representation based on farm survey data.

Figure 3.2 shows the final path model structure applicable to intentions to use landscape elements, technological SI measures, and regional marketing of the current non-users.

Table 3.5 presents the respective estimated path coefficients for all three models. We find mixed evidence for the influence of currently used complementary measures on intentions to broaden the SI portfolio in the future. Positive experience with currently used complementary SI measures is positively associated with farmers' considerations to use landscape elements (0.25) or technological SI measures (0.17). However, there is no evidence for a direct effect from the current use of SI measures. The coefficient for landscape elements is comparably large (0.16) but statistically not significant. The currently used portfolio of complements has a negative influence on considering regional marketing in the future (-0.20). Adoption of regional marketing depends strongly on the economic and environmental sustainability attitudes of farmers. Economic sustainability attitude also affects the intention to use technological SI measures (0.14). Social interaction constructs have comparably small path coefficients.

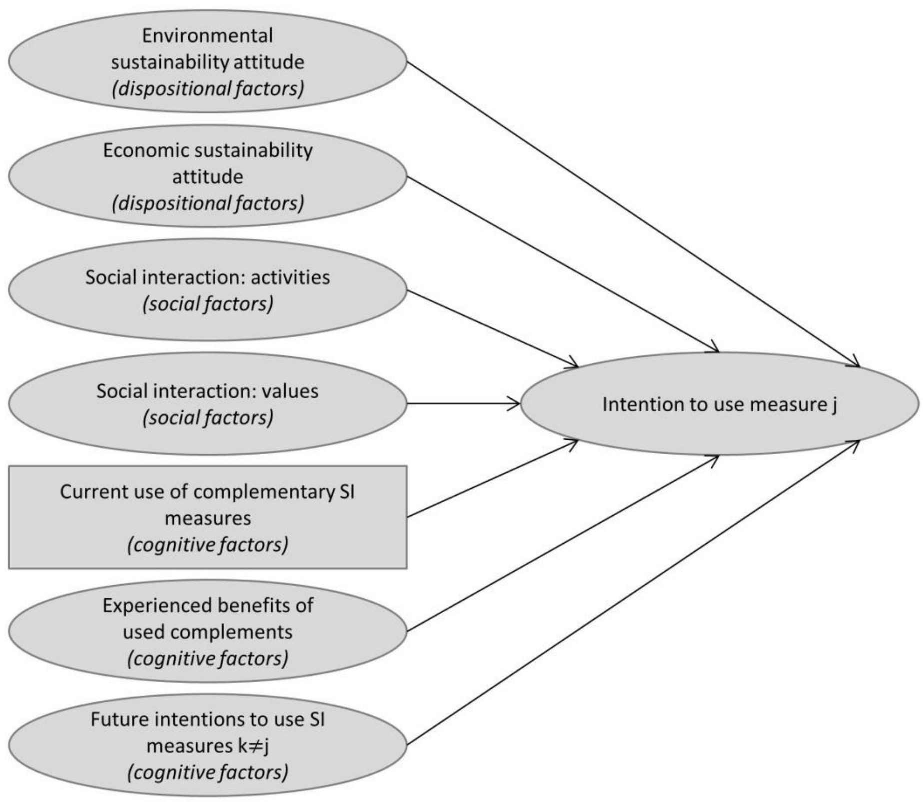


Figure 3.2 Structural model specification estimated with PLS-SEM.
Note: Unobserved constructs in circles; observed constructs in boxes.
Source: Own representation.

Table 3.5 Structural model path coefficients indicating constructs' influence on the intention to use SI measure j prospectively

Construct	SI_tech	SI_land	SI_mark
Environmental sustainability attitude	0.02 (0.66)	-0.20 (0.01)	0.17 (0.00)
Economic sustainability attitude	0.14 (0.01)	-0.12 (0.18)	0.27 (0.00)
Social interaction: activities	0.03 (0.62)	0.07 (0.37)	0.07 (0.00)
Social interaction: values	0.03 (0.67)	0.02 (0.89)	-0.14 (0.15)
Current use of complementary SI measures	0.03 (0.68)	0.16 (0.17)	-0.20 (0.00)
Experienced benefits of used complements	0.17 (0.02)	0.25 (0.02)	-0.04 (0.50)
Future intentions to use other SI measures	0.23 (0.00)	0.30 (0.00)	0.06 (0.32)
N	266	170	267
R^2	0.13	0.23	0.11

Note: p-values in parentheses; N= number of observations.
Source: Own representation based on farm survey data.

3.5 Discussion

We observe a low tendency among farmers to prospectively broaden their portfolios of SI measures in the study area. For agronomic- and pasture-related SI measures, an upper sealing seems to be reached with potential user shares of 83% and 59%, respectively. Agronomic SI measures comprise well-known practices in the scientific literature (cf. Wezel *et al.*, 2015). This result is consistent with the opinions of the focus group participants, who see agricultural SI measures and pasture grazing as well-established in their region. Adoption barriers for other SI measures appear severer; despite less than half (landscape elements) or less than a quarter (technological measures and regional marketing) of the surveyed farms using these measures, only an additional 9% plan to do so prospectively. Lower user shares prevail among those SI measures that are costly to implement, such as precision farming or regional marketing (cf. e.g., Reimer *et al.*, 2012).

Our modelling results indicate that farmers decide on SI measures by adjusting the SI portfolio using an interrelated decision process. Interrelationships, indicated by correlations among decisions on SI measures, partly reflect overlaps between the groups of SI measures, for instance the overlap seen between agronomic measures and landscape elements. Precision farming and regional marketing decisions are also positively correlated with decisions on agronomic SI measures and landscape elements. Pasture grazing is revealed as a measure driven by farm specialisation, one less likely to be used in combination with other measures. Although we broke down the decision problem into two quantitative modelling steps, our results indicate a gradual decision process for the SI measures portfolio. This was also found by Lemken *et al.* (2017) and Van Hulst and Posthumus (2016) concerning the adoption of single sustainable practices. We link the current portfolio and intentions to use additional SI measures, via farmers' perceived economic and environmental benefits from currently applied SI measures; hereby, a positive link is observed for technological measures and landscape elements. We find a direct negative correlation between farmers' intention to adopt regional marketing and the use of complementary SI measures.

Among behavioural models, the Reasoned Action Approach emphasises the role of perceived behavioural control to affect behavioural intentions. Behavioural control is comprised by feelings to be able to decide on the use or non-use of a measure, as well as feelings concerning capability of the successful implementation (Fishbein and Ajzen, 2011). Our results go further, indicating adoption intentions might not only relate to control beliefs of a single measure, but also to experiences of currently used portfolios of SI measures. Previous experience with similar measures or innovations has already been found to play a role in adoption decisions (Sauer and Zilberman, 2012; Yeboah *et al.*, 2015). Perceived advantages have been used as explanatory factors for adoption of single measures (e.g., Reimer *et al.*, 2012), but not according to a portfolio perspective. Taking a portfolio perspective on sustainable practice adoption means that spill-over effects, from positive perceptions of a SI measure to the adoption of others, become important model relationships. The explored interrelationships indicate multifaceted decisions, feedback effects between SI measures, and complexity in the adoption process. Our findings thus contribute to studies indicating that complexity in decision-making poses a core challenge when studying adoption barriers (e.g., Aubert *et al.*, 2012; Pathak *et al.*, 2019 for precision farming). Likewise, further research underpinning feedback effects among measures supports the development of policy intervention schemes to foster large-scale uptake. Farm open days (e.g., Läpple *et al.*, 2017) and information provision through adopters (e.g., Raymond and Brown, 2011) are suggested as raising adoption rates of sustainable practices, because farmers experience the benefits. The leverage of such interventions would be even larger when leading to additional adoption-related portfolio effects.

Using the reviewed literature as support, we find attitudes towards environmental and economic sustainability as explaining intentions to adopt (cf. Dessart *et al.*, 2019). In behavioural experiments, farmers' environmental attitudes have been shown to positively influence the adoption of sustainable practices (Thomas *et al.*, 2019). In our model, environmental attitudes also positively influence regional marketing decisions; we find economic sustainability attitude, comprising attitudes towards personal innovativeness, risk, and regional economic responsibility, to be relevant to intentions to use regional marketing and precision agriculture. These results are in line with those of Barnes *et al.* (2019) for precision farming, and Läpple and Kelley (2015),who emphasise the relevance of farmers' risk attitudes.

Another of our findings is that a high percentage of adopters in the same postal code area increases the likelihood to choose one of the five SI measures. Läpple *et al.* (2017) relate such patterns to learning effects and similar regional circumstances. Peer-to-peer learning is suggested as a starting point for increasing the percentage of SI adopters (cf. Buckwell *et al.*, 2014). This indicates that peer-to-peer exchanges potentially offer intervention points that trigger changes in social norms (cf. Nyborg *et al.*, 2016) which in turn foster SI uptake. We also use information, provided by the data at hand, on social interactions among farmer, but cannot rely on any measure of perceived norms nor perceived societal pressure. Mills *et al.* (2017) differentiate community norms, representing pressure from the farmers' personal reference group, from societal norms, representing consumer influence and public concerns and appreciation. Important social referents, which should be considered in future research, include family members (Burton and Wilson, 2006), other farmers (Kuhfuss *et al.*, 2016), or professional advisory services (Blackstock *et al.*, 2010).

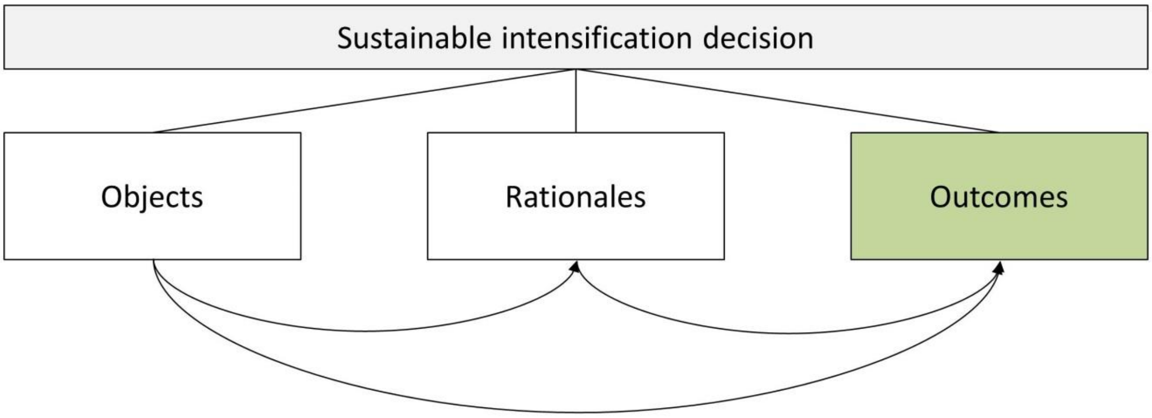
This chapter presents an example on how to beneficially connect quantitative and qualitative data, as well as different statistical approaches, for a refined understanding of farmers' use of SI measures from a regionally contextualised portfolio. Mixed-method approaches such as employed in this paper are shown to be promising in various contexts: Leonhardt *et al.* (2019) explain results on soil conservation behaviour by adding information gained from qualitative interviews; Senger *et al.* (2017) identify farmers' diversification outcomes in preliminary interviews before conducting a quantitative analysis of uptake patterns. Barnes *et al.* (2019) note the lack of studies using qualitative data in determining adoption barriers for precision farming. Our modelling process can be replicated for different regions and contexts for further insights into the interrelations of different types and groups of SI measures.

In a study on farm business enlargement decisions, Hansson and Ferguson (2011) show that understanding a theory's individual components is a necessary pre-step for suggesting an integrated model. In social sciences and economics, advocacy for pre-registration studies and pre-analysis plans increases that require explorative testing of envisaged model specifications (cf. Olken, 2015). Testing additional model relationships also allows for the refining of existing modelling frameworks (cf. Reimer *et al.*, 2014). In our exploratory analysis, based on a dataset at hand, we find support for behavioural factors shaping adoption intentions, but propose feedback effects between SI measures as modelling extension. Additionally, a more detailed investigation of the pressure exerted by different social referents is likely to be a further important component in behavioural models for sustainable practices with externalities (Wauters and Mathijs, 2014). Carroll and Groarke (2019) advocate the development and use of standardised theory-based frameworks for effectively targeting farmers' behavioural change. An additional aspect for future research following Yoder *et al.* (2019) would be a feedback effect on how experienced benefits from having implemented SI measures in turn influence long-run sustainability attitudes of farmers.

3.6 Conclusions

A reason for limited evidence on intervention schemes to achieve large-scale adoption of sustainable practices may be that existing theoretical models are designed for single measures. The aim of this chapter is to gain insights on interrelated decision-making as to whether farmers use and broaden portfolios of sustainable intensification measures. We studied five SI measure groups for the northern German Plain based on cross-sectional farm survey data. SI measures embrace agronomic, technological, and regional marketing approaches, as well as landscape elements and pasture grazing. Identified interrelationships among decisions are measure specific. In a multivariate probit model controlling for farm(er) characteristics, we found complementary relationships among decisions to use SI measures; the exception is pasture grazing, for which landscape elements is substitutional. Using path models, we find that farmers' beneficial experiences with currently used complementary measures positively influence their intentions to use landscape elements and technological SI measures. Our explorative procedure offers insights for refining existing models for behavioural rationales, and we propose integrating beneficial experiences with complementary measures as a promising line of further research.

4 Sustainable intensification farming as an enabler for farm eco-efficiency?



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4.1 Introduction

Food production systems face the challenges of meeting global food demand triggered by a growing population (Tilman *et al.*, 2011), public interest in climate-friendly, sustainable production practices (Feldmann and Hamm, 2015), and limited natural resources (Cordell *et al.*, 2009; Popp *et al.*, 2014). It has been argued that intense farming practices contribute to loss of biodiversity, greenhouse gas emissions and groundwater contamination (Foley *et al.*, 2011) and that the ecological improvements in farming typically associated with extensive or organic production often cannot maintain productivity levels (Ponisio *et al.*, 2015).

Thus, 'smart' combinations of organic systems and intensive farming practices are being pursued as potential solutions (Meemken and Qaim, 2018). The concept of sustainable intensification (SI), originally proposed to foster sustainable yield growth in developing countries (e.g., Pretty, 1997b), has been postulated as a partial solution (Godfray and Garnett, 2014). SI aims to balance the trade-off between production economics and environmental sustainability. From a farming perspective, the balance is achieved by agricultural production practices that improve either economic or environmental outcomes without reducing either (Pretty and Bharucha, 2014). Important agronomic examples of SI measures include resource-saving wider crop rotations, reduced tillage, integrated pest management and technological solutions for input management such as precision agriculture (cf. Chapter 2 of this dissertation for an overview on SI measures). Overall, SI production systems aim to reduce environmental harm while maintaining yield levels (Pretty, 2018), closing yield gaps (Mueller *et al.*, 2012), offsetting the negative effects of agricultural land use (Baulcombe *et al.*, 2009), and ensuring incomes which sustain rural economies (Godfray and Garnett, 2014).

Evaluations of the goal attainment of SI measures are mainly based on field trial data (e.g., Paul *et al.*, 2015; Townsend *et al.*, 2016) or simulation-based approaches (e.g., Mao *et al.*, 2015; Devkota *et al.*, 2016) with a focus on yield effects. Holistic, farm-level approaches, however, seem underrepresented. Some studies of developing countries find improvements in farms' economic performance from adopting SI measures (e.g., Kassie *et al.*, 2015b), whereas farms in northern countries focus more on ecological improvements without sacrificing economic performance (Godfray and Garnett, 2014).

Barnes and Thomson (2014) and Areal *et al.* (2018) develop indicators to track the economic and ecological farm outcomes and assess SI for European case studies, but do not link indicator outcomes to the adoption of specific SI measures.

In this chapter, we provide evidence for ***research question 3:*** *How does the use of sustainable intensification measures affect farm environmental outcomes?* Therefore, we aim to evaluate how the adoption of SI measures contributes to farms' environmental performance in the north-western European context. We propose to use the concept of eco-efficiency to evaluate the success of SI measures. Eco-efficiency is defined as producing more output using fewer resources with reduced environmental harm (Schmidheiny, 1993). At the firm level, eco-efficiency captures the improvement of environmental outcome while maintaining economic output in a cost-effective manner (cf. Kuosmanen and Kortelainen, 2005). Using static and dynamic production frontier models, Callens and Tyteca (1999), Tyteca (1999), Kuosmanen and Kortelainen (2005) and Kortelainen (2008) propose a radial eco-efficiency measure based on non-parametric Data Envelopment Analysis (DEA). These approaches have been applied to agricultural production (e.g., Pérez Urdiales *et al.*, 2016). As one of the few exceptions relating eco-efficiency to SI, Gadanakis *et al.* (2015) suggest that arable farms in the United Kingdom could reduce eco-inefficiencies via the SI measures. However, their approach does not consider the possible extent of this reduction.

Following the idea of sequential preferences of Asmild and Hougaard (2006), farm managers first aim at technical efficiency and improvements in the economic output dimension. Second, after meeting a certain economic threshold, and depending on their environmental preferences, they improve the environmental output. We model the improvement potential in the ecological output dimension by using directional DEA (cf. Picazo-Tadeo *et al.*, 2012). The resulting eco-inefficiency scores reflect the improvement potential as the distance of actual to potential production in the ecological direction while maintaining the economic output.

We aim to quantify how the SI measures reduce the ecological improvement potential and could provide more ecological output at no economic cost. We treat SI measures as a different technology compared to traditional farming practises. We hypothesize both technologies enveloped by a system frontier and take a meta-frontier approach (cf. O'Donnell *et al.*, 2008). The system frontier offers the highest possible outcomes in either direction, where the SI adopters are hypothesized to largely determine the system frontier in the ecological direction. We use the ecological output on the system frontier as a reference to identify farms' improvement potentials.

Observed differences in the ecological improvement potentials between SI adopters and non-adopters could also be related to structural differences of the two groups, such as natural and socio-economic conditions (e.g., Kassie *et al.*, 2015b) or environmental preferences (e.g., Omer *et al.*, 2010). In line with Mayen *et al.* (2010), linking the technology adoption decision and eco-efficiency analysis is a pre-condition to identify causal relationships. Therefore, this chapter further contributes to answer ***research question 2***: *Which factors influence farmers' choices of sustainable intensification measures and are these choices interrelated?;* and draws on evidence of Chapter 3 on SI adoption rationales.

By enhancing the theoretical framework of Chabé-Ferret and Subervie (2013), we acknowledge the role of farmers' preferences and assume a representative farmer will first decide whether to choose the SI technology. Subsequently, the farm household maximizes its utility, where the adopters voluntarily constrain production to reduce the improvement potential compared to their own non-SI reference improvement potential. We account for selectivity issues by comparing the eco-efficiency scores of SI farms with farms of a matched control sample (cf. Bogetoft and Kromann, 2018). To understand how the SI measures improve eco-efficiency, we use rich survey data on lowland farming systems in the northern German Plain collected in 2017 (Weltin *et al.*, 2019).

This chapter makes three important contributions. To our best knowledge, it is the first study to provide a meta-frontier approach to measure improvement potentials in the direction of the ecological output. Second, based on a theoretical framework, it uses a matching algorithm to generate a control sample that reduces potential bias and offers a causal interpretation of differences in eco-efficiency through SI measures. Third, the meta-frontier approach separates the differences in improvement potentials between the SI adopters and non-adopters into a *technology effect* and a *performance effect.*

Differences between the group-specific frontiers of the SI adopters and non-adopters indicate whether SI is promising by offering a frontier closer to the meta-frontier (*technology effect*). How efficiently a farm operates within its chosen technology indicates the *performance effect*.

The remainder of this chapter is structured as follows. Section 4.2 elaborates on the theoretical background and introduces the hypotheses. Section 4.3 describes the empirical model, the data, and the case study. Section 4.4 discusses the results. Section 4.5 concludes and offers suggestions for future research.

4.2 Theoretical framework

We enhance the behavioural model of Chabé-Ferret and Subervie (2013) to frame the decision to adopt sustainable intensification measures, identify the causal effects of SI on farms' eco-efficiency, and derive hypotheses.

We model a representative farm i that produces output $\boldsymbol{Y}$, with an economic Y_{econ} and ecological dimension Y_{ecol}. We use agronomic SI measures to categorize the SI technology and the traditional technology and denote the respective production technology sets by Ψ_j with $j = [0;\ 1]$, where $j = 0$ indicates production without SI measures and $j = 1$ indicates the SI-adjusted production system. In both technology sets, farm i chooses a variable input X and on-farm labour H to produce output $\boldsymbol{Y}$. Fixed inputs $\boldsymbol{I}$, such as human and physical capital, and unobserved factors $\boldsymbol{\varepsilon}$, such as land quality, weather conditions or managerial ability, enter the production possibility sets[9]:

$$\Psi_j = [(X, H, \boldsymbol{I}, \boldsymbol{\varepsilon}, \boldsymbol{Y})|X, H, \boldsymbol{I}, \boldsymbol{\varepsilon}\ can\ produce\ \boldsymbol{Y}]. \tag{4.1}$$

Following O'Donnell *et al.* (2008), the group-specific technologies, Ψ_j, determine a common production system frontier, Ψ_m, enveloping the SI and non-SI production frontiers as illustrated in Figure 4.1. The solid black line represents the system frontier in the two-output setting and the dashed lines represent the two group-specific technologies. Farms producing on the system frontier will be eco-efficient. The distance

[9] Where possible, the farm index i is suppressed for notational simplicity.

between a farm's actual production and the system frontier will capture this farm's improvement potential, i.e., eco-inefficiency. We measure eco-inefficiency as the distance of actual production in the direction of the ecological output while maintaining the economic outcome within a directional distance function (e.g., Picazo-Tadeo *et al.*, 2012). In Figure 4.1, the distance between A and A'' denotes the improvement potential for a non-SI farm and A' to A'' denotes the improvement potential for an SI farm.

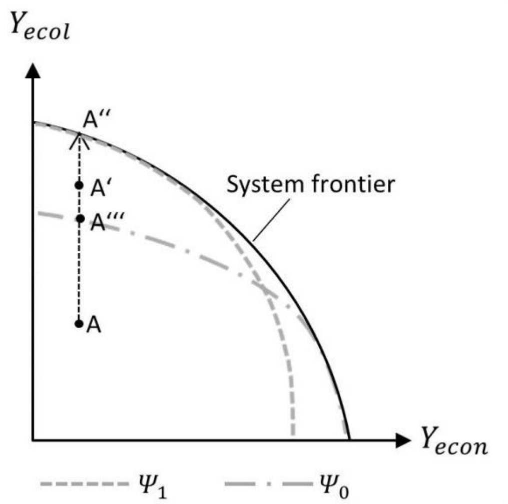


Figure 4.1 System frontier and the two group-specific frontiers, non-SI ($\boldsymbol{\Psi_0}$) and SI ($\boldsymbol{\Psi_1}$).
Note: Ecological improvement potential is $\overline{\mathbf{AA''}}$ under non-SI and $\overline{\mathbf{A'A''}}$ under SI. Eco-efficient production implies an improvement potential of $\overline{\mathbf{A'''A''}}$ under non-SI and $\overline{\mathbf{A''A''}}$ under SI.
Source: Own representation.

When SI measures yield ecological improvements, eco-efficient production under Ψ_1 should provide higher ecological output for a given economic output level than eco-efficient production under Ψ_0. In Figure 4.1, A''' denotes that the eco-efficient producing farm under Ψ_0 can still improve in the ecological direction by $\overline{A'''A''}$, and A'' denotes that that the eco-efficient producing farm under Ψ_1 produces on the system frontier and fully exploits the improvement potential in the ecological direction. We frame the *technology effect* as:

Hypothesis 4.1: *The SI frontier locates in the direction of the ecological output closer to the system frontier. Hence, the SI adopters in this direction determine the system frontier.*

Adopting SI measures, therefore, could reduce the ecological improvement potential compared to not adopting SI. The observed and measurable respective improvement potential of a farm, denoted as $\tilde{Y}_j$, results from two sequential decisions. First, the farm household's decision to adopt SI determines the possible improvement in the ecological direction by the respective group-specific frontier. Second, the farm household's decision regarding input allocation and intensity determines how eco-efficiently to operate with the chosen technology.

We follow Chabé-Ferret and Subervie (2013) and solve backwards. Based on maximising a utility function U, the farm household evaluates optimized production input levels X_j^* and on-farm labour time allocation H_j^* for both the SI and non-SI technology. These optimized production levels determine the optimal outputs, and thus the improvement potentials $\tilde{Y}_j^*$ for both cases. Both X_j^* and H_j^* are functions of the exogenous variables, such as prices, consumption shifters, preferences and fixed inputs, as denoted by g_j and h_j, respectively. Following Asmild and Hougaard (2006), we assume that sequential preferences guide the farm household's decision to adopt SI measures. Hence, the SI farm aims to reduce the improvement potential in the ecological direction compared to their non-SI reference situation. In their decision-making, farms use the results from previous years and their experience to estimate the reference improvement potential: $\tilde{Y}_0^* = \tilde{Y}_0(X_0^*, H_0^*)$.

The farm household's utility maximisation problem is given by:

$$\max_{C,L,H,H_{off},X} U(C, L, H, X, \boldsymbol{S}, \boldsymbol{\eta}) \tag{4.2}$$

subject to:

$$Y_{econ} = f_j(X, H, \boldsymbol{I}, \boldsymbol{\varepsilon}, Y_{ecol}) \tag{4.3}$$

$$C = pY_{econ} - p_x X + wH_{off} \tag{4.4}$$

$$T = L + H + H_{off}\,, \tag{4.5}$$

where utility U depends on levels of consumption C, leisure L, variable input X, and on-farm labour hours H. The latter two reflect the dependence of utility on the farm household's preference or distaste for certain input compositions. Consumption shifters $\boldsymbol{S}$, such as age or education, and unobservable taste shifters $\boldsymbol{\eta}$, such as ecological preferences or idiosyncratic non-farm profit opportunities also enter U. Equation (4.3) gives the transformation function in an explicit form regarding Y_{econ} according to the implicit function theorem (e.g., Sauer and Wossink, 2013). Equation (4.4) states that the farm household sells Y_{econ} for price p with input costs at price p_x and quantities X. The farm generates additional income from H_{off} hours of off-farm work remunerated by wage rate w. Equation (4.5) constrains the total available time T of hours for on- and off-farm labour and leisure time.

Optimal input levels under non-SI are given by:

$$X_0^* = g_0(p, p_x, w, T, \boldsymbol{I}, \boldsymbol{S}, \boldsymbol{\eta}, \boldsymbol{\varepsilon}) \tag{4.6}$$

and $H_0^* = h_0(p, p_x, w, T, \boldsymbol{I}, \boldsymbol{S}, \boldsymbol{\eta}, \boldsymbol{\varepsilon})$. (4.7)

When applying SI, the farm's input allocation will be guided such that the improvement potential in the ecological direction, $\tilde{Y}_1$, will not exceed the optimized improvement potential of the reference situation, $\tilde{Y}_0^*$. This provides an additional voluntary constraint to the utility maximization problem. The constraint becomes applicable when the farm adopts SI ($D = 1$), where the reference improvement potential enters as a constant:

$$D(\tilde{Y}_1(X, H, \boldsymbol{I}, \boldsymbol{\varepsilon}, \boldsymbol{Y}) - \tilde{Y}_0^*) \leq 0. \tag{4.8}$$

The voluntary constraint of equation (4.8) enters the first-order conditions:

$$\frac{\partial U}{\partial C}\left(p\frac{\partial f_j}{\partial X} - p_x\right) + \frac{\partial U}{\partial X} - \lambda\left(\frac{\partial \tilde{Y}_1(X, H, \boldsymbol{I}, \boldsymbol{\varepsilon}, \boldsymbol{Y})}{\partial X}\right) D = 0 \tag{4.9}$$

$$\frac{\partial U}{\partial C}\left(p\frac{\partial f_j}{\partial H} - w\right) + \frac{\partial U}{\partial H} - \lambda\left(\frac{\partial \tilde{Y}_1(X, H, \boldsymbol{I}, \boldsymbol{\varepsilon}, \boldsymbol{Y})}{\partial H}\right) D = 0, \tag{4.10}$$

where λ denotes the respective Lagrangian multiplier.

Therefore, the optimized input choices under SI depend on the reference situation's improvement potential, $\tilde{Y}_0^*$. This counterfactual improvement potential works as a lower bound against which farms compare the respective improvement potential under SI. If the constraint is binding ($\lambda \neq 0$), the farm will adjust X and H but may be compensated by increases in utility. If the constraint is not binding ($\lambda = 0$), the farm has no costs in terms of the constrained use of $X$and H when applying SI. Optimized input and labour allocation under SI are given by:

$$X_1^* = g_1\left(p, p_x, w, T, \boldsymbol{I}, \boldsymbol{S}, \boldsymbol{\eta}, \boldsymbol{\varepsilon}, \tilde{Y}_0^*\right) \tag{4.11}$$

and $H_1^* = h_1(p, p_x, w, T, \boldsymbol{I}, \boldsymbol{S}, \boldsymbol{\eta}, \boldsymbol{\varepsilon}, \tilde{Y}_0^*)$. (4.12)

We note that if the farm's expected improvement potential under SI, $\tilde{Y}_1^*$, remains insufficiently large enough to increase utility compared to $\tilde{Y}_0^*$ according to the environmental preferences, the farm will not adopt ($D = 0$) and equation (4.8) becomes irrelevant.

We only observe the outcome of the decision process and measure the observed improvement potential, $\tilde{Y}_j$, which depends on whether the farm chooses to apply SI measures. The farm decides on SI based on the indirect utilities, V_1 and V_0. Indirect utilities depend on the same variables as $\tilde{Y}_1^*$ and $\tilde{Y}_0^*$. The implementation of SI may, however, induce search, implementation or information cost denoted by V. Cost V potentially varies with education and experience and reduces indirect utility when choosing SI. The farm will adopt SI ($D = 1$) when the expected increase in indirect utility outweighs the cost of adoption:

D=$\boldsymbol{1}[E[V_1 - V_0|\boldsymbol{Z}] - V \geq 0]]$, (4.13)

where $\boldsymbol{Z}$ denotes the determinants of the farm's adoption decision. The determinants may coincide with the determinants of input choices, such as environmental preferences, consumption shifters or fixed inputs. Since the adopters and non-adopters may systematically differ regarding their environmental preferences, we need to ensure comparability between the two groups prior to assessing the observed improvement potentials.

Thus far, we have assumed eco-efficient production under the respective technology. In the short-run, however, inefficiencies within the chosen technology may occur and the adjustment costs of technology adoption may be tolerated (Ang and Oude Lansink, 2017). Ignoring the possible inefficiencies of SI adopters within their technology particularly would bias the retrieved improvement potentials. A fully efficient non-SI farm could have a lower improvement potential compared to a weakly efficient SI-farm. We illustrate this *performance effect* in Figure 4.2 for two examples of non-SI reference situations of farms A and B. At best, if farm A could achieve A'', the improvement potential turns to zero. Otherwise farm A may only be able to reduce the improvement potential up to a point A', which is also achievable in the non-SI technology, due to eco-inefficiencies within the SI technology. Farm B is eco-efficient within the non-SI technology but could exhibit eco-inefficiencies in the SI technology such that it is unable to move to a point B’ that reduces the improvement potential. A performance B’’’ under SI corresponding to the ecological output level of A’ could even increase farm B’s improvement potential.

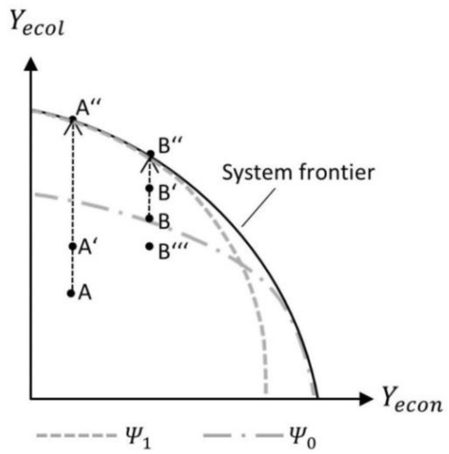


Figure 4.2 Improvement potentials for different reference situations of farms A and B.
Note: SI adoption may shift farm production to A’ and B’ with reductions in improvement potential. B’’’ represents a situation when eco-inefficiencies in the SI technology increase the improvement potential compared to B.
Source: Own representation.

We develop the following hypotheses concerning the improvement potential of SI adoption and non-adoption:

Hypothesis 4.2a: *At the mean, for the same economic outcome, SI adopters produce at a lower ecological improvement potential than comparable non-adopters.*

Hypothesis 4.2b: *If SI adopters have a low within-technology performance in the chosen technology and comparable non-adopters have a high within-technology performance, the non-adopters have lower improvement potential than the adopters in some cases.*

4.3 Data and empirical approach

4.3.1 Survey, measures and summary statistics

We use data taken from a survey of farming practices between February and June 2017 in areas with abundant peatlands in the northern German Plain. The areas require adapting farming practices to meet Germany's climate protection and biodiversity goals (TEEB, 2015). The specific areas were the federal states of Brandenburg, Mecklenburg Western Pomerania, Saxony-Anhalt, Lower Saxony and Schleswig Holstein. For Brandenburg, Mecklenburg, and Western Pomerania, we used farms located in areas with at least 20 % peatland area and 1,000 ha of peatlands in total, and those with more than 5,000 ha of peatlands in total, based on postal code. Additional respondents were recruited via farmers' associations in all five federal states. From the 464 observations in the spatial expansion (cf. Figure 4.3), we used the 410 farms for which we observed adoption decisions for SI measures, and excluded 26 farms below 5 ha, for a total of 384 farms. The full questionnaire can be found in Appendix B.

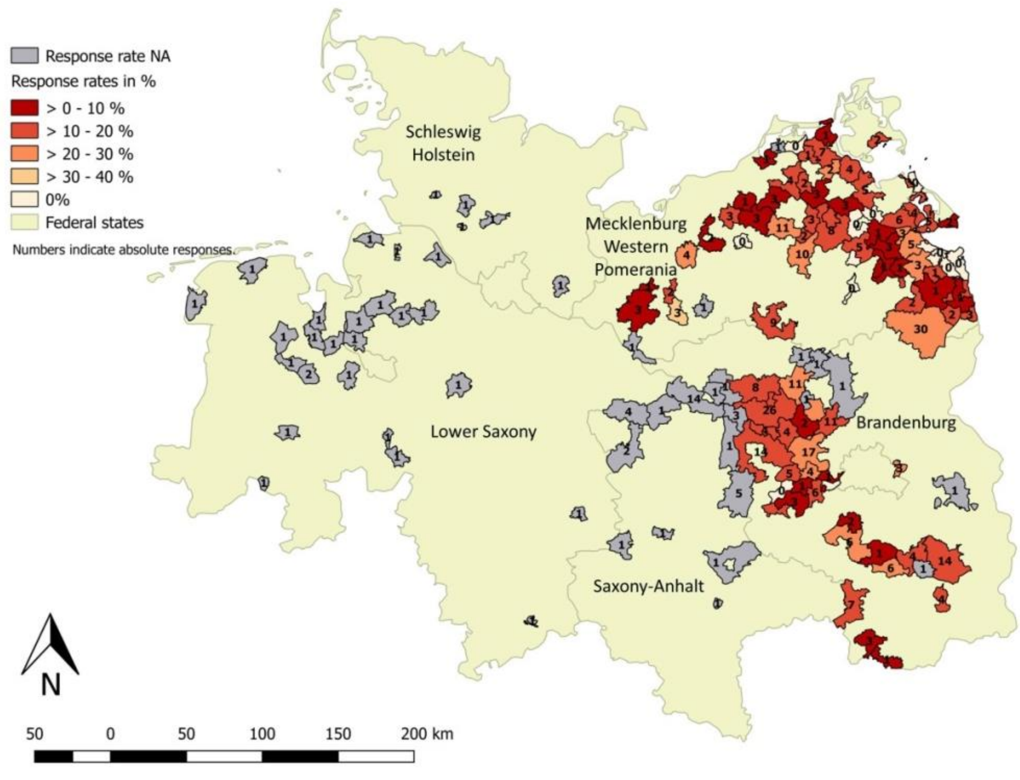


Figure 4.3 Map of the spatial expansion of the sample and response rates.
Note: 22 farms are excluded from the map as they did not provide their postal code.
Source: Weltin and Zasada (2018).

Following Kuosmanen and Kortelainen (2005) in their approach to eco-efficiency analysis, we consider economic outputs, and positive or negative environmental outputs without modelling all inputs in the production process. We use the agricultural area as input to ensure that improvement potentials are derived for farms of comparable size. For the economic output dimension, Y_{econ}, we use a farm profit indicator provided on an ordinal scale with twelve categories[10]. We primarily focus on farmland and crop diversity as the ecological output of farming and use indicators classified as indirect or related to farmland management that correlate with direct biodiversity outcomes (cf. Bockstaller *et al.*, 2011). Following a whole-farm approach by Gibson *et al.* (2007), we measure farm-level heterogeneity between different landscape elements (on-farm diversity) and the diversity within each land use type (on-land diversity). We assign equal weight to both aspects of diversity in the final ecological output indicator (cf. Gan *et al.*, 2017). Table 4.1 reports the calculations of the indicators.

Landscape simplification has been identified as a strong predictor for losses in species richness (Dainese *et al.*, 2019). Therefore, we consider farm-level heterogeneity and include all types of cropped and non-cropped areas on the farm. We use the Simpson diversity index (cf. Van Eck and Koomen, 2008) to capture the shares of arable land, extensive grassland and other grassland. For non-cropped land, we observe the presence but not the amount of fallow land and flower or buffer strips. Acknowledging the high value of these semi-natural areas for biodiversity (Weibull *et al.*, 2003; Herbst *et al.*, 2017), we assign them 50 % of the weight in the overall indicator for on-farm diversity.

For on-land diversity, we measure the biodiversity in arable land by the number of different crops grown on the farm within a year (Matson *et al.*, 1997). For grassland, we include the share of permanent grassland to total grassland. In addition to biodiversity, this indicator captures the carbon sink function of grassland (Barnes and Poole, 2012). We use the farms' shares of permanent pasture that exceed regional averages to capture a biodiversity surplus extending the indicator of Areal *et al.* (2012). The third grassland indicator is the abundance of peatlands extensively managed or in conditions

[10] Categories: 1 loss/smaller than 0 €; 2 up to 10,000 € ; 3 up to 20,000 € ; 4 up to 40,000 € ; 5 up to 60,000 € ; 6 up to 80,000 €; 7 up to 100,000 €; 8 up to 120,000 €; 9 up to 140,000 €; 10 up to 200,000 €; 11 up to 250,000 €; 12 more than 250,000 €.

close to nature, with a high impact on carbon capture and biodiversity (TEEB, 2015). We weight the three grassland indicators equally. We weight the indicators for arable and grassland by the respective share of each land-use type on the farm in the composite indicator for on-land diversity.

Table 4.1 Environmental output indicators

Indicators	Calculations
On-farm diversity	
Normalised Simpson diversity index $a_{i,norm}$	$a_i = 1 - \sum_k p_{ik}^2$; p_{ik} share of land use type k on farm i; k includes arable land, permanent grassland and other grassland. $a_{i,norm.} = \frac{a_i}{1-\frac{1}{k}}$ normalises a_i to the interval [0;1].
Presence of fallow b_i	Indicator turns to 1 if fallow is present on farm i.
Presence of flower and buffer strips c_i	Indicator turns to 1 if flower or buffer strips are present on farm i.
Aggregated indicator on-farm diversity	$1/2\ a_{i,norm.} + 1/4\ b_i + 1/4\ c_i$
On-land diversity	
Crop diversity in arable land d_i	Number of crops grown on farm i per year divided by the sample maximum.
Permanent grassland e_i	Share of permanent to total grassland on farm i.
Biodiversity surplus of permanent grassland f_i	$f_i = \frac{q_i - \overline{q}_{reg.size}}{1 - \overline{q}_{reg.size}}$; q_i share of permanent pasture to UAA of farm i; $\overline{q}_{reg.size}$ average share of permanent pasture to UAA by federal state and farm size class retrieved from Destatis (2018); f_i is set to 0 if $\frac{q_i - \overline{q}_{reg.size}}{1 - \overline{q}_{reg.size}} < 0$.
Extensively managed peatlands g_i	Share of near-natural or extensively managed peatland area to total peatland area on farm i.
Aggregated indicator on-land diversity	$\frac{\text{arable land}_i}{\text{UAA}_i} d_i + \frac{\text{total grassland}_i}{\text{UAA}_i} \frac{1}{3} (e_i + f_i + g_i)$

Note: All indicators are in the interval [0;1].
Source: Own representation based on reviewed literature.

Based on an extensive literature review and workshop discussions with farmers and stakeholders in the Rhinluch region (cf. Weltin *et al.*, 2018b), we selected six SI measures aimed at enhancing diversity: (i) reduced tillage, (ii) intercropping, (iii) growing legumes, (iv) integrated pest management, (v) grazing, and (vi) extensive use of grassland. Since SI measures best exploit their benefits through combination (Benton *et al.*, 2003; Kassie *et al.*, 2015b), we defined a farm as an SI adopter that chooses the SI technology if it applied at least two SI measures. Table 4.2 characterises SI and non-SI farms and gives summary statistics.

Regarding the extent of their business operation, SI farms are more likely to be full-time farms and operate a larger area. SI farmers tend to have higher education, degrees in agriculture, and use professional extension services compared to non-SI farmers. We further characterise farmers by self-assessment statements on their values and attitudes.[11] The SI farmers show a stronger affinity than non-SI farmers for the regional entrepreneurship variable. Differences in environmental awareness and regional attachment, however, are small.

Table 4.2 Summary statistics for SI and non-SI farms

	SI farms			Non-SI farms		
Variables	N	Mean	Std. Dev	N	Mean	Std. Dev
Used agricultural area [ha]*	304	513.00	698.60	79	79.21	163.80
Business type [1=full-time; 0=part-time]*	303	0.71	0.46	78	0.36	0.48
Organic farming [1=yes; 0=no]	303	0.20	0.40	77	0.19	0.40
Specialisation in arable farming [1=yes; 0=no][a]	304	0.34	0.47	77	0.25	0.43
Labour intensity [workforce/ha UAA][b]*	288	0.04	0.06	70	0.11	0.14
Use of extension services [1; 5][c]*	298	2.91	1.23	76	2.34	1.25
Formal agricultural education [1=yes; 0=no]*	295	0.77	0.42	74	0.57	0.50
Highest educational degree [1; 3][d]*	296	2.39	0.86	76	1.99	0.93
Farming experience [years]	295	27.62	13.03	72	26.50	14.77
Regional attachment [1; 10][e]	294	8.95	1.83	76	8.87	1.93
Environmental awareness [1; 10][e]	291	7.12	2.58	75	6.75	2.80
Entrepreneurial attitude [1; 10][e]*	288	6.34	2.13	71	4.82	2.21
Economic output: profit indicator [1; 12]	271	4.63	3.80	69	2.84	2.81
Ecological output indicator [0; 1]	295	0.44	0.13	76	0.30	0.19

*Wilcoxon rank sum test for differences between groups has a p-value < 0.05.
[a] According to the self-assessment of the farmer.
[b] Workforce below 1 person is summarized as 1.
[c] 1=never; 2=sometimes; 3=occasionally; 4=often; 5=very often
[d] 1=lower secondary or intermediate education or no degree; 2=high school degree; 3=university degree
[e] Self-assessment questions for which respondents indicated the degree of agreement on a scale from 1=fully disagree to 10=fully agree
Source: Own representation based on farm survey data.

4.3.2 Empirical model specification

The observed improvement potential, $\tilde{Y}_j$, corresponds to the eco-inefficiency to the system frontier, thus, higher eco-efficiency scores imply reduced improvement potential. We use a meta-frontier approach to measure the eco-efficiency scores to the system frontier and within-technology performance to the group-specific frontiers (e.g., Gómez-Limón *et al.*, 2012). We are interested in the possible proportional increase of the ecological output dimension while keeping economic output constant and staying in

[11] Five self-assessments include environmental awareness, regional attachment, the endeavours to adopt innovations, bear business risks and contribute to regional economic development. The latter three form the variable regional entrepreneurship. Factor analysis supports the separation of the five self-assessments into three distinct constructs (cf. Part I of Appendix D).

the respective production set Ψ_m or Ψ_j. Hence, we rely on directional distance functions (DDF) following Picazo-Tadeo *et al.* (2012). We specify the DDF with outputs $\boldsymbol{Y} = (Y_{ecol}, Y_{econ})$, agricultural area input Q and define the direction vector $g_y(Y_{ecol}, 0)$:

$$\vec{D}_{ecol,j}(Q, \boldsymbol{Y};\ g_y) = Sup\left[\beta_{ecol,j}: \left(\boldsymbol{Y} + \beta_{ecol,j}\ g_y\right) \in \Psi_m\right]. \quad (4.14)$$

For within-technology performance, Ψ_j in equation (4.14) replaces Ψ_m. Symbol $\beta_{ecol,j}$ represents the proportion by which Y_{ecol} could be increased to reach the respective frontier. The ratio $1/(1 + \beta_{ecol,j})$ determines the fraction of the feasible output realized by the farm, i.e., eco-efficiency in the interval $[0; 1]$. The following relationship holds: eco-efficiency to the system frontier equals the meta-technology ratio (MTR) multiplied by group-specific eco-efficiency. The MTR is the farm's distance to the system frontier if the farm produced on its group-specific frontier (Gómez-Limón *et al.*, 2012). An MTR of 1 implies that the group-specific frontier coincides with the meta-frontier and offers to assess the *technology effect* of SI. Eco-efficiency in the economic direction may be similarly calculated by setting the direction vector to $g_y(0, Y_{econ})$.

We use directional Data Envelopment Analysis (DEA). DEA is flexible, requires no functional form assumptions and allows the inclusion of both monetary and non-monetary inputs and outputs (Charnes *et al.*, 1978). We opt for a full disposable hull technology to obtain the most cautious estimates of the eco-inefficiency scores, i.e., the respective improvement potentials. Since DEA results are sensitive to outliers with regard to the inputs and outputs (Bogetoft and Kromann, 2018), we use the minimum covariance determinant estimator by Rousseeuw and Driessen (1999) for outlier control. We estimate robust Mahalanobis distances to assess how far away an observation is situated from the centre of the data (cf. Part II of Appendix D for details). We observe land, profit and biodiversity indicators for 325 observations and eliminate 17 outliers. We use the R packages *Benchmarking* and *Robustbase* to perform the calculations.

The eco-efficiency approach offers an estimate of the improvement potential of adopters and non-adopters, but unobservable determinants, e.g., preferences, of the voluntary SI adoption decision may affect the differences in the observed outcomes and lead to biased estimates. The SI adopters may differ in their farm(er) characteristics from the non-adopters so that a comparison of the observed improvement potentials will not suffice to identify the causal differences. Sub-sample homogeneity is a precondition for the causal interpretation of outcomes when selectivity issues prevail (Bogetoft and Kromann, 2018). By using a matching approach with farm(er) characteristics $\boldsymbol{Z}$ as covariates we can generate a control group that resembles the group of SI adopters in these core characteristics and then compare the eco-efficiency of adopters and counterfactual non-adopters.

Matching methods have been used to reduce the differences between groups with stochastic frontier approaches (Mayen *et al.*, 2010; Bravo-Ureta *et al.*, 2012) and DEA (Bogetoft and Kromann, 2018). We use kernel density matching based on Mahalanobis distances and the Epanachnikov kernel function. Mahalanobis distances deliver robust results in small samples (Zhao, 2004). Kernel matching allows us to assign several control observations to each SI adopter, thus reducing the variance of the estimation. We determine the bandwidth of the estimator by cross-validation to minimize the mean squared error regarding the averages of the covariates. We use the command *kmatch* in Stata14 and generate a sample of control observations from the weighted averages of the matched controls.

The matching variables $\boldsymbol{Z}$ consist of farmers' education and experience and the farm characteristics, i.e., full-time operation, specialisation in arable and organic farming, and labour intensity, to reflect the intensity of the farming operation and input use. The use of advisory services represents the external knowledge input in the farm business. The variables have proven relevant in selection equations for farm management decisions or in two-stage eco-efficiency approaches (e.g., Gómez-Limón *et al.*, 2012; Chabé-Ferret and Subervie, 2013; Gadanakis *et al.*, 2015). Farmers' preferences and sustainability attitudes represent an additional component of decision-making (e.g., Jongeneel *et al.*, 2008; Hansson *et al.*, 2018). While attitudes have been shown to affect eco-efficiency outcomes (e.g., Pérez Urdiales *et al.*, 2016), we do not observe them directly and therefore use farmers' self-assessments as proxies. We exclude 43 observations with missing values for a total sample of 265 observations (cf. Table D1 in Part III of Appendix D for descriptive statistics).

Output indicators, definitions of SI adopters and non-adopters and specific characteristics of our sample (cf. Section 4.3.1) may affect the sensitivity of eco-efficiency scores (cf. Areal *et al.*, 2018; Gadanakis and Areal, 2018). Therefore, we conduct a robustness analysis and repeat the eco-efficiency analysis for different modes of sampling, spatial coverage, farm types, SI definitions, and weighting of the environmental output indicator.

4.4 Results and discussion

The covariate balance indicates the comparability of SI farms and matched control non-SI farms. Standardized differences are mostly small and all below the rule-of-thumb value of 0.25 (Stuart, 2010). Table E.1 summarizes the standardized differences and group means before and after matching in Appendix E. On average, an SI adopter has 3.78 control observations as matches. We exclude the 28 SI farms and three non-SI farms out of common support to increase the precision of estimates following Lechner and Strittmatter (2017). The final sample for DEA consists of 193 SI farms and their matched control non-SI farms. Table 4.3 summarizes the results.

Table 4.3 Eco-efficiency scores in the direction of the ecological output for SI adopters and their matched controls

	SI farms		Non-SI farms	
	Mean	Std. dev.	Mean	Std. dev.
Meta-technology ratio (MTR)	1.00	0.00	0.77	0.13
Eco-efficiency to system frontier/ improvement potential	0.75	0.18	0.61	0.15
Eco-efficiency to group-specific frontier/ within-technology performance	0.75	0.18	0.80	0.14
N	193		193	

Note: Wilcoxon rank-sum test for differences between SI and non-SI farms has a p-value < 0.01 for all three measures.
Source: Own representation based on farm survey data.

Table 4.3 indicates that SI farms mainly determine the system frontier (*Hypothesis 4.1*): the MTR is equal to 1 for 64% of SI farms and almost 1 for 36% of other SI farms (std. dev. 5.73e-08). In other words, if all SI farms were eco-efficient to their group-specific frontier, they would also be eco-efficient to the system frontier. Adopting SI measures offers to reduce the environmental improvement potential in the ecological direction to the system frontier. The average MTR is 0.77 for non-SI farms, where only 20 have a MTR of 1. In other words, few farms could be eco-efficient to the system frontier without adopting SI. We use the distributions of the eco-efficiency scores to test the differences in the location of the frontiers. Based on a Kolmogoroff-Smirnov test, we reject the null hypotheses that the distributions of eco-efficiency scores to the group-specific frontier and system frontier are identical for non-SI farms (D=0.65; p=0.00). For SI farms (D=0.01; p=1.00), the system and SI frontiers coincide and we find evidence for the *technology effect* of SI.

Table 4.3 shows that SI farms are on average more eco-efficient to the system frontier (0.75) than matched control non-SI farms (0.61). SI farms produce 75 % and non-SI farms 61 % at the mean of the potentially possible ecological output, keeping land and economic output constant. The average difference in eco-efficiency is 0.13 score points. The result shows that SI is associated with a reduction of the ecological improvement potential (*Hypothesis 4.2a*). The results of our robustness check reveal stable differences between SI adopters and matched non-adopters in eco-efficiency to the system frontier, ranging between 0.11 and 0.15 score points (cf. Appendix E Table E.2).

Using the matching approach allows us to compare the full distributions of the eco-efficiency scores (Bogetoft and Kromann, 2018). Figure 4.4 shows that while 31 SI adopters and 10 non-adopters produce on the system frontier, the respective eco-efficiency scores are heterogeneously distributed, although SI measures offer a higher potential to produce on the system frontier. The results of robustness check show similar patterns to Figure 4.4 (cf. Appendix E Figures E.1 a–f).

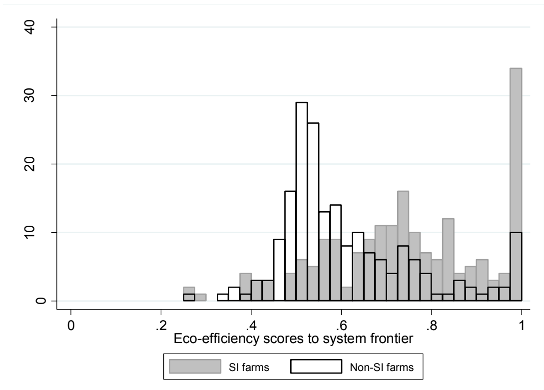
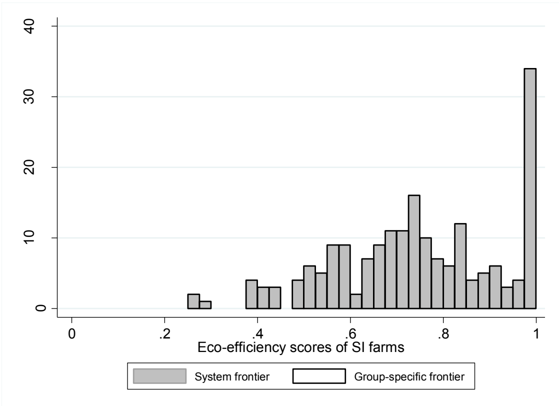
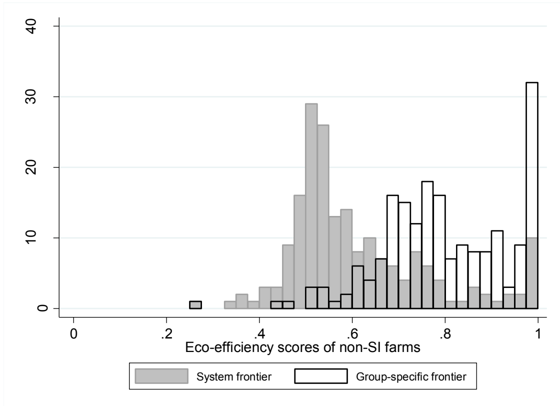


Figure 4.4 Distribution of eco-efficiency scores to the system frontier for SI and non-SI farms.
Source: Own representation based on farm survey data**.**

Eco-inefficiencies within the group-specific technology cause SI farms' deviations from the system frontier; 84% of SI farms could improve their within-technology performance. Figure 4.5a shows that the eco-efficiency scores in the ecological direction of SI farms to their group-specific frontier are almost identical to their scores to the system frontier. Figure 4.5b shows that improvement potentials for non-SI farms result from a mixture of inefficiencies to the group-specific frontier and the fact that the non-SI technology does not allow reaching the system frontier. Non-SI farms' average eco-efficiency score regarding the group-specific frontier is 0.80.



a) For SI farms



b) For non-SI farms

Figure 4.5 Distribution of eco-efficiency scores to the system and group-specific frontier.
Source: Own representation based on farm survey data.

Figure 4.6 shows that 74% of SI farms have a higher eco-efficiency score to the system frontier than their respective matched control non-SI farms. The increase in eco-efficiency is on average 0.24 and maximal 0.54 score points. The farms move closer to the system frontier and reduce their improvement potential by adopting SI. Figure 4.6 also shows that 25 % of SI farms have a lower eco-efficiency score than their matched control farms. The decrease in eco-efficiency is on average 0.17 and maximal 0.45 score points. Eco-inefficiencies within the SI technology impede possible reductions in improvement potentials offered by the outwards shift of the SI frontier, at least in the short-run. This result supports the *performance effect* that a low within-technology performance could lead to increases in the improvement potential when choosing SI measures for some farms (*Hypothesis 4.2b*).

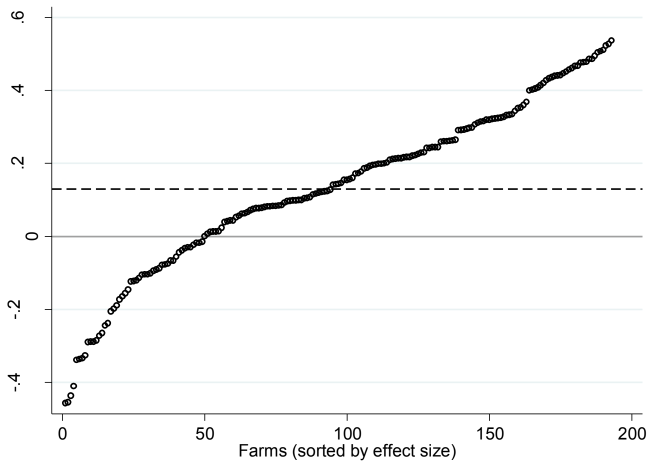


Figure 4.6 Difference in eco-efficiency to the system frontier for SI farms compared to their matched control non-SI farms.
Note: Farms are sorted by the effect size. The dashed line indicates the average difference of 0.13 score points.
Source: Own representation based on farm survey data.

The heterogeneous distribution of the eco-efficiency scores is consistent with previous research on multidimensional performance assessments (e.g., Sidhoum *et al.*, 2019). We suggest that the heterogeneity and increasing improvement potential for some SI adopters may be attributed to insufficient understanding of complex SI production systems (Kassam *et al.*, 2011), and that biodiversity effects may only be achieved in the long-run (Gabriel *et al.*, 2013).

The results also support our assumption of sequential preferences found by Asmild and Hougaard (2006). Table E.3 in Appendix E shows that SI farms have a higher mean eco-efficiency score to the system frontier in the direction of the economic output (0.54) than without SI (0.39). Farm managers may need to become more efficient in an economic direction prior to adopting SI measures and improving in the ecological direction. Rational inefficiencies described by Hansson *et al.* (2018) may explain a larger distance to the frontier in an economic direction than in an ecological direction. As mentioned in Section 4.2, farmers may rationally decide to prioritise ecological outcome above economic efficiency gains when non-financial values are included in their utility function. Eco-inefficiency in the economic direction may also represent an adjustment cost as farmers reduce their ecological improvement potential (Ang and Oude Lansink, 2017).

Germany's farmers may receive some compensation for adopting SI measures from the voluntary agri-environmental schemes of the European Union's Common Agricultural Policy. Financial support does not seem to be generally associated with SI adoption, however; only 31% of SI adopters in our dataset receive payments for two or more SI measures, and 36% receive no payments for their SI measures. Refusal to accept monetary compensation may be related to the policy itself, or farmers' perceived restrictions or objections to government control (Burton and Schwarz, 2013). Our findings are in line with previous studies of behavioural economics showing that farmers are willing to contribute to environmental protection even if it is costly and not remunerated (cf. Thomas *et al.*, 2019).

4.5 Concluding remarks

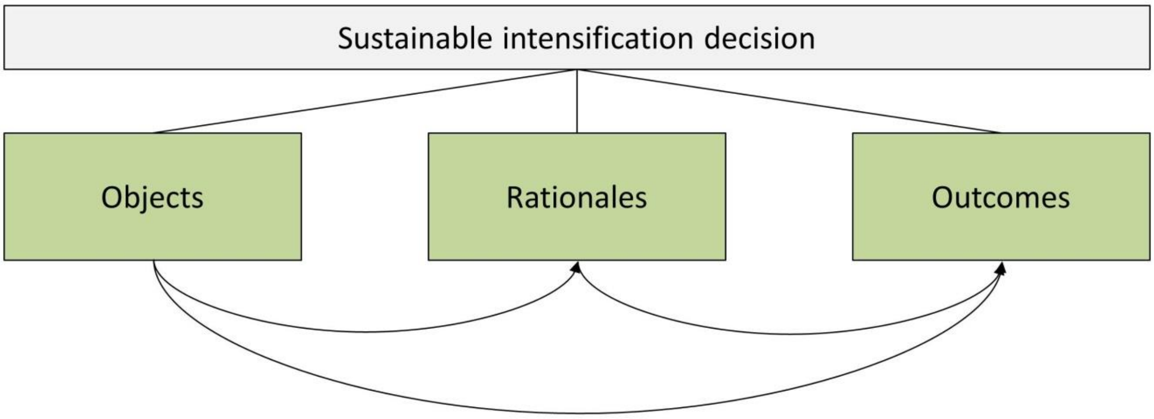
In this chapter, we assess the contributions of agronomic SI measures to ecological sustainability in agricultural land-use based on eco-efficiency. Enhancing the theoretical framework of Chabé-Ferret and Subervie (2013), we model farmers' decisions to choose different production possibility sets reflecting adoption and non-adoption of SI measures. Eco-efficiency scores to a meta-frontier, the system frontier, as estimated by directional DEA capture the farms' ecological improvement potential. A matching approach allows us to ensure comparability of SI adopters and non-adopters. We use a survey of farms in northern Germany to determine SI measures and a composite indicator for biodiversity as an ecological outcome.

On average, SI farms have higher eco-efficiency scores to the system frontier, i.e., reduced improvement potential. The mean difference in the eco-efficiency scores between SI farms and non-SI farms is 0.13 score points although a low within-technology performance of SI farms may increase improvement potential. The majority (84%) of SI farms in the dataset are eco-inefficient to the overall system frontier, but they would produce on the system frontier if they were eco-efficient within the SI technology. The findings suggest that the adoption of SI measures offer a way to reduce improvement potential that SI farms often do not use to the full extent. The probability to reach the system frontier without adopting SI is small. Similar to previous studies of eco-efficiency and SI, farmers' characteristics and preferences need to be acknowledged to adequately compare the differences in improvement potential.

The chapter has the following limitations. SI measures are indicated in the dataset as being present or absent and the extent and quality of their applications are summarized in a single SI technology. This approach allows a straightforward assessment of the results but may contribute to the heterogeneity in improvement potential. The diversity of farm types may further contribute to this heterogeneity. Additionally, biodiversity is assessed by proxy indicators derived from the farm survey data. A trade-off exists in the number of observations and degree of detail of the output measures. Exact outputs can only be measured directly on the farm (e.g., Picazo-Tadeo *et al.*, 2011; Schulte *et al.*, 2018) and comprehensive indicator sets and appropriate weights are difficult to develop (Franks, 2014). Still, our main results prove robust to alternative definitions of the SI adopters, farm heterogeneity, and weighting of the outcome indicator.

We suggest several topics for future research. A large-scale consistent set of data and sustainability indicators could facilitate analysis beyond the regional or country scale. Kelly *et al.* (2018) suggest enhancing the Farm Accountancy Data Network in that regard for Europe. Longitudinal data would allow a detailed analysis of adjustment cost and account for long-run economic planning, sequential preferences or longer time horizons to realize environmental effects. This could lead, in turn, to a robust basis for the design of incentives to ensure that environmentally promising measures lead to more environmentally beneficial outcomes. Result-based support measures that reward farmers for achieving ecological improvements are being discussed in Europe as policy options for promoting biodiversity (e.g., Burton and Schwarz, 2013). Fostering pro-environmental and entrepreneurial behaviour could reinforce adoption decisions and support environmental performance.

5 Discussion



In this chapter, we discuss the main outcomes of the three empirical studies presented in chapters 2–4. First, we summarize the key findings regarding the three sub-questions and how these relate to the overall research question (Section 5.1). We continue with the methodological and theoretical contributions of the analyses (Section 5.2). As the SI concept receives increasing interest among policymakers, we discuss potential policy intervention schemes to foster uptake of sustainable intensification measures and exploitation of farms' improvement potentials (Section 5.3). Subsequently, we discuss the limitations of the results presented and identify realms for future work (Section 5.4). We conclude with the main contributions of the dissertation to different fields of research (section 5.5).

5.1 Summary of key results

We discuss the main findings of the three empirical studies presented in chapters 2–4 and their contributions to answer the three research questions. Figure 5.1 summarizes the research process and results.

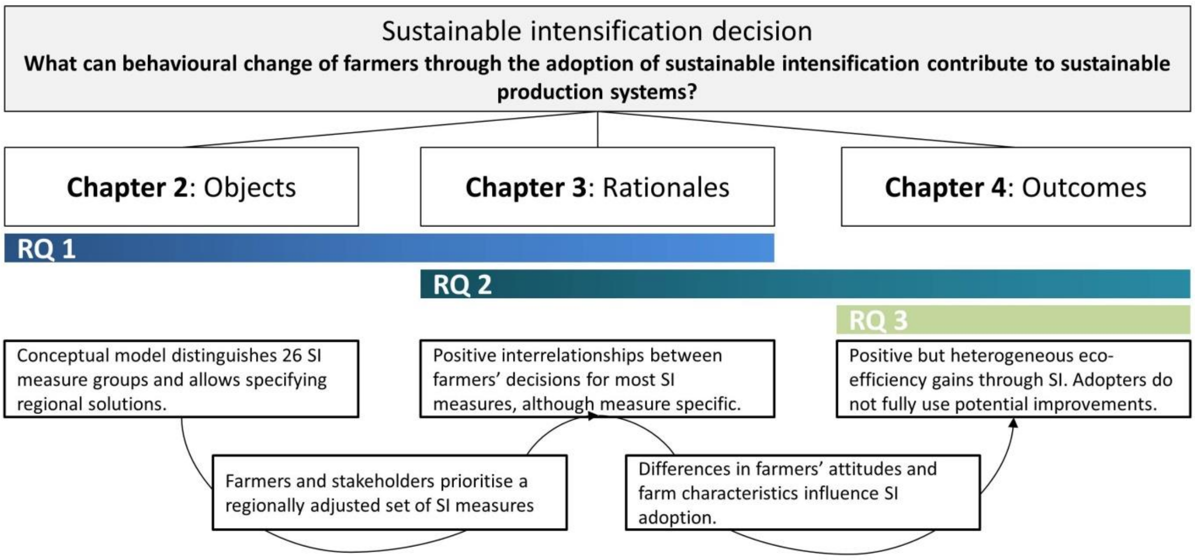


Figure 5.1 Summary of the results of the empirical studies.
Source: Own representation.

Research question 1: *Which measures are subsumed under the sustainable intensification concept and how can regionally adjusted portfolios of sustainable intensification measures be identified?*

Compiling and clustering the main SI measures through a systematic literature review of 349 scientific papers (1997–2016), the results of Chapter 2 show that SI measures can be classified according to their spatial scale, from farm to landscape level, and their activity scope, from spatial to structural optimisation. Thus a conceptual model is postulated to describe the practical meaning of SI, consisting of four fields of action with altogether 26 groups of SI measures. The conceptual model proved to be easy to grasp for practitioners. Based on the four fields of action, stakeholders identified and prioritised SI measures for their regional context in moderated focus groups in four European case study regions. The specific SI measures identified varied according to the regional context. However, in all four regions stakeholders named measures for all fields of action and pointed to the field of regional integration as the most important one for the future.

In this regard, the systematic literature review shows a science-practice gap. The literature focuses mainly on single SI measures of one field of action and addresses the farm level more frequently than the regional landscape scale. The results also show that the SI literature is rather incoherent: key publications frequently cited within the body of SI literature are lacking, in the time frame up to 2008 the term was almost not used and if so targeted to developing countries. Increase and regional spread of SI research started in 2014 and the disciplinary diversity is high. Researchers seem to put different practical meaning to SI, without having achieved an integrated view. Striving for coherence in the understanding of SI is necessary in order to derive useful policy-related implications from the SI concept and contribute to its further theoretical development. The conceptual model of SI measures is suggested as a step in that direction.

For empirical applications, the conceptual model proved useful, for instance, when selecting the SI measures for the analysis of farmers' adoption behaviour and rationales in Chapter 3. To study the determinants of farmers' adoption decisions, the measures of highest priority in the stakeholder process serve as input. In the surveyed areas of the northern German Plain, the share of farmers using regional marketing, having shown the highest future priority in the workshop in the Rhinluch region (cf. Table 3.1), is low (25%). The scope for further development remains low measured by the share of farmers in the survey who intend to adopt in the future (9%). The stakeholder information thus sketches potential SI options for the region but does not necessarily serve as a good predictor for adoption rates.

Research question 2: *Which factors influence farmers' choices of sustainable intensification measures and are these choices interrelated?*

Chapter 3 analyses interrelations in farmers' decisions to use SI measures. Our explorative results indicate that the adoption rationales may not be sufficiently analysed taking an isolated view on single SI measures. Studying SI adoption behaviour requires acknowledging decision-making for a mix of measures. Overseeing and assessing the effects of SI measures prior to adoption on the cost and administrative structures of the farm business as well as resulting changes in time and labour allocation is likely to be difficult for the farmer. This makes the decision process complex. We explore some of the potential interactions and feedback effects among decisions on SI measures in a two-stage modelling approach.

For five regionally prioritised SI measures for the northern German Plain case study area[12], the results of a multivariate probit model controlling for farm(er) characteristics (1st modelling stage) indicate a positive relationship among decisions for most SI measures except pasture grazing. Thus, there several complementary measures seem to exist that are likely to be used together and form regional SI farm portfolios. Farmers are likely to broaden these portfolios in a gradual adoption process. Farmers' use of complementary SI measures and their associated positive perceptions of economic and environmental outcomes of these measures partially serve as predictors of farmers' intentions to adopt additional SI measures in the future. We estimate these relations in partial least squares path models (2nd modelling stage). We do not find evidence for a direct positive effect of using complementary measures on the intention to broaden the SI portfolio. However beneficially experienced outcomes positively influence intentions

[12] Agronomic SI measures, pasture grazing, precision farming, landscape elements, regional marketing.

to adopt for landscape elements and precision farming. This indicates that farmers' knowledge and experience of economic and environmental benefits may support further broadening of the SI portfolio. With respect to future intentions to use regional marketing, there is a direct negative effect of using complementary measures from the first modelling stag. The results of both modelling stages jointly suggest that the adoption behaviour of SI measures should be assessed as an interrelated complex decision problem, albeit the interdependences of decisions are measure-specific. Based on our explorative approach, we propose integrating and testing these aspects in established models of adoption behaviour.

Behavioural factors, specifically the economic sustainability attitude of farmers, play an important role for decision-making. Environmental awareness is comparably less relevant in our models. The study on the resulting farm outcomes from adopting different combinations of agronomic SI measures (Chapter 4) confirms that adopters and non-adopters are rather similar in their environmental attitude. In contrast adopters see themselves much more as innovative entrepreneurs who are willing to accept risk and regional social responsibility than non-adopters.

Research question 3: *How does the use of sustainable intensification measures affect farm environmental outcomes?*

To study the environmental improvement a farmer may achieve through using SI measures, Chapter 4 theoretically frames SI and non-SI production as different technologies. A meta-frontier, that is the production possibility frontier of the system, envelopes the SI and non-SI production frontiers. We enhance the theoretical model of Chabé-Ferret and Subervie (2013) to explain a farmers' choice of the SI technology and resulting distance of current farm production to the system frontier in the direction of an environmental output. This distance describes a farm's improvement potential or eco-inefficiency. Due to the dependencies of the SI decision on farm, farmers' demographic and behavioural characteristics demonstrated in Chapter 3, systematic differences of adopters and non-adopters may bias their differences in eco-efficiency outcomes. The theoretical model builds the baseline for a matching approach to allow for a causal interpretation of eco-efficiency differences between SI adopters and non-adopters. We generate a control group of non-adopters that resembles the adopters in their key characteristics.

Eco-inefficiencies in the direction of the environmental output to the different frontiers are compared for SI adopters and their matched controls. To reduce the complexity of the analysis, biodiversity indicators are used to measure the environmental outcome based on the farm survey data and SI measures only include agronomic measures. The results of Chapter 4 allow for three conclusions regarding the environmental improvement through SI: First, the SI adopters mainly determine the meta-frontier, that is eco-efficiently producing SI farms have a lower improvement potential (distance to the meta-frontier) than most eco-efficiently producing non-SI farms. Second, the average improvement potential is lower for SI adopters. Thus, choosing SI leads to the production of higher ecological outcomes without economic losses compared to the non-SI reference situation. However, third, eco-efficiency of adopters is heterogeneously distributed and some adopters have a low within-technology performance. That means, they do not fully exploit their potential for improvement. Thus in some cases, high performing non-adopters outperform comparable adopters. Therefore, at least in the short-run, eco-inefficiency of adopters plays a crucial role and may prevent environmental improvement.

By summing up the findings on the three questions, the **overarching research question** **"***What can behavioural change of farmers through the adoption of sustainable intensification contribute to sustainable production systems?"* can be answered:

First of all, the three studies show that before coming to a sound judgement the relevance of farmers' perspectives to evaluate SI measures has to be acknowledged: farmers determine which SI measures are selected and considered relevant for a specific regional contexts as well as if and how measures are applied. Decisions on SI measures are taken in joint consideration of a portfolio of interrelated measures. The results show the potential environmental benefit of SI measures in terms of increasing farm environmental efficiency to increases the sustainability of the production system. However, these benefits are not as easily realised as some field trials, simulation studies or spatial extrapolation analyses might suggest. Farmers have valid rationales whether or not to apply a certain mix of SI measures. Implementation can be hampered by eco-inefficiencies that need to be overcome to fully exploit improvement potentials.

5.2 Theoretical and methodological contributions

Decision objects

A systematic literature review is an established method of gaining structured insight into a research field or topic (Littell *et al.*, 2008). Besides the assessment of temporal and geographical trends, we analyse the discourse by a citation analysis assessing the citations of each article within the 349 selected SI papers and the citations by other articles outside the field. This allows showing the closeness and connectedness of a research field and to identify key papers. Additionally, the outreach and importance of each article beyond the studied field can be put into perspective.

A contribution is the conceptual model of SI. Chapter 2 shows in line with other studies (e.g., Wezel *et al.*, 2015; Bernard and Lux, 2016) that a diversity of definitions and understandings of SI exist. Hence, the systematic and transparent procedure taken allows for a more structured understanding on the practical approaches subsumed under the SI concept. For transparency, the assignment of SI practices to groups of measures and fields of action is published in a data article (Weltin *et al.*, 2018a and Appendix A). Although we used a systematic process of cross-checking, discussion of critical cases, and reclassification of SI measures in a team of interdisciplinary researchers to reach consistency of results, inspired by Gao *et al.* (2017), some SI measures' classification may be subject to debate. The data article allows for discussion and reassessment of critical cases. Thus the conceptual model is suggested as a flexible frame for the assessment and regional selection of SI measures. Future research on new SI measures could enhance this frame.

Decision rationales

Regarding model development, Carroll and Groarke (2019) call for the development of standardised theory-based frameworks to effectively target farmers' behavioural change. With the estimated path models, we provide explorative evidence on behavioural determinants of adoption decisions such as the sustainability attitudes. By using this explorative step-wise modelling approach, we follow the ideas that separate models are needed as a pre-step for an integrative model (Hansson and Ferguson, 2011) and new variables and model relationships need to be tested to refine existing approaches (Reimer *et al.*, 2014). We propose the model constructs of currently using complementary SI measures and the economic and environmental benefits experienced with these SI measures to be important explanatory factors for choosing to use SI measures. Existing behavioural approaches and models could be refined for portfolio choices and feedbacks effects among decisions.

From a methodological perspective, we underscore the value of path modelling when a dataset is explored that consists of a variety of potentially interesting variables that represent latent factors. The benefits of explorative path modelling for theory and model development have been highlighted, albeit review studies show that these are frequently not sufficiently highlighted and exploited in applied studies as reasons to opt for a PLS exploratory approach (cf. Hair *et al.*, 2012). We also show that mixed-method approaches of quantitative and qualitative data are useful to integrate place-based and regional aspects that are partly neglected in current models of decision-making (cf. Barnes *et al.*, 2019). Thereby we add to findings on mixed-method approaches for instance provided by Leonhardt *et al.* (2019) and Senger *et al.* (2017).

Decision outcomes

With the study on environmental outcomes through applying SI measures presented in Chapter 4, a theoretical model is presented based on Chabé-Ferret and Subervie (2013). The original model is enhanced by including different production technologies and suggesting a meta-frontier framework to assess differences in outcomes depending on farmers' technology choices. The model builds a theoretical baseline to analyse the sensible connection of measure uptake and sustainability outcomes. We theoretically disclose potential selectivity issues to be considered in the empirical analysis.

Methodologically, we use a matching approach to make SI adopters and non-adopters comparable and estimate distances to production frontiers by non-parametric DEA. Both methods per se are well established, the former in causal effect studies (cf. Blundell and Costa Dias, 2009) and the latter in efficiency analyses (cf. Coelli *et al.*, 2005). However, there are few cases where both are combined. Mayen *et al.* (2010) assess efficiency differences for organic and non-organic farms with prior propensity score matching but use a stochastic frontier analysis. Bogetoft and Kromann (2018) discuss the benefits of combining matching and DEA approaches. A major benefit is the possibility to compare the full distribution of efficiency scores of adopters and non-adopters additional to average differences allowing for a more detailed interpretation of results. Chapter 4 makes use of this option. Thus our study provides an additional case using directional DEA eco-efficiency scores with matching.

5.3 Policy implications

The results of the stakeholder process presented in Chapter 2 show that the concept of sustainable intensification can be translated into practical action and encompasses regional solutions for practitioners. However, as a concept SI mainly receives attention from scientists and policymakers. The interest of the latter has broadened from a developing country perspective (e.g., FAO, 2011; FAO, 2013) to the European policy level (e.g., Foresight, 2011; Buckwell *et al.*, 2014). Fostering measures that lead to environmental improvements without economic losses appears to be an ideal case for policymakers. Chapter 4 indicates the superiority of the SI production technology in terms of environmental efficiency compared to the non-SI technology for agronomic SI measures. At the same time, the adoption rates and the associated positive economic and environmental perceptions of farmers vary strongly across SI measures (cf. Chapter 3). Assuming a public interest in the broader and more effective SI implementation, in this section, we focus on the policy implications of the results in Germany and Europe.

So far, the main instruments of the European Common Agricultural Policy (CAP) aiming to incentivise changes towards environmentally friendlier farm management are the voluntary agri-environmental schemes (AES) rooted in its second pillar. These action-based schemes imply that farmers apply a certain pre-defined measure or management approach, such as extensive grassland management or organic farming, and receive a financial compensation representing the cost of implementation and associated income loss. In the programming period 2014 to 2020, the EU has provided ca. 12 billion Euros annually for such measures (Hasund and Johansson, 2016). With the introduction of so-called eco-schemes with the post-2020 CAP, the EU broadens the scope of action-based schemes. The eco-schemes are also voluntary, albeit member states can pay a higher incentive than the associated income loss. Eco-schemes will be payed from the pillar one budget of the CAP. They are designed by the member states according to regional environmental needs (European Commission, 2019). In general, the post-2020 CAP transfers responsibility from the EU to member states in order to design the CAP support for their countries and herewith opens new possibilities for place-based approaches.

AES have been criticized to be insufficient to foster successful implementation of sustainable practices. They have been found to hamper innovation by the farmer due to their prescriptive character and do not result in a long-term behavioural change (Burton and Schwarz, 2013). Points of critique from an ecological perspective include that AES only lead to marginal or moderate environmental improvements on field level and lack quantifiable objectives to evaluate outcomes (Kleijn *et al.*, 2006). The results of the study on eco-efficiency improvements through SI measures (Chapter 4) show that farmers apply SI measures often without taking available compensation through AES. Many farmers do not attain the maximum potential environmental improvement possible. Whether eco-schemes, that are not substantially different to AES, will bring substantial changes appears questionable.

In line with calls for a 'culturally sustainable' agricultural policy that leads to farmers' long-term behavioural change (Burton and Paragahawewa, 2011) and based on the results of the three studies presented in this dissertation, we discuss some policy intervention schemes that might be a meaningful extension of current CAP instruments. These should foster not only adoption rates of SI measures but also incentivise adoption in an environmentally efficient way. We consider (1) the reward of environmental outcomes through result-based AES, (2) communication strategies that raise awareness for potential benefits of SI measures, and (3) the inclusion of farmers and land managers in the selection and design of policy measures through multi-stakeholder governance processes.

1) Remuneration of the provision of environmental outcomes

Payment for the provision of environmental outcomes is the main idea of result-based AES of which a few prototypes exist in Europe (cf. Burton and Schwarz, 2013). Farmers receive a payment if they cross a certain threshold of a preferably easy-to-measure environmental outcome indicator. An example is the ‘flowering meadows programme’ for species rich pasture in the German federal state Baden Wuerttemberg. Farmers receive a payment if they have at least four plant species out of a reference list of 20 on their land (Fleury *et al.*, 2015).

Current adoption rates and acceptance of agronomic SI measures are high but their implementation success could be improved, as shown in Chapter 4. Result-based payments could incentivise more effort to maximise benefits. In addition, with very different combinations of SI measures at hand a farmer would have the freedom to choose the best mix with regard to the farm type, personal talents and regional context. This is in line with the advantages that are discussed for result-based AES: They are flexible in terms of measure implementation to achieve specific local goals and promise a more efficient resource allocation (Hasund, 2013). They represent a cultural change of viewing the farmer as the innovator who contributes to environmental outputs and could increase farmers’ intrinsic motivation to participate (Russi *et al.*, 2016). Result-based rewards communicate farmers’ contribution to environmental outcomes as an important product for society giving a direct and positive feedback to their work and effort (Burton and Schwarz, 2013).

On the contrary, result-based payments increase the risk for the farmer as the payment is not secure. Another challenge lies in monitoring and developing appropriate indicators (Burton and Schwarz, 2013). Finding robust indicators for biodiversity outcomes was also a challenge in this dissertation with regard to the eco-efficiency analysis (cf. Chapter 4). App-based schemes as well as satellite images and remote sensing are suggested as remedies (Hasund, 2013). To reduce scepticism among farmers, some of the existing schemes are accompanied by advice and training offers (Schroeder et al., 2013). These could be a promising approach to promote the spread and successful implementation of SI measures through communication and awareness-raising.

2) Communication and awareness-raising

Communication strategies can be targeted towards the recipients who are expected to realize the behavioural change, that is farmers, and towards the general public to raise the recognition of producers' efforts. Dessart *et al.* (2019) describe knowledge as an important cognitive factor: The awareness of farmers of sustainable practices, their economic and ecological benefits, but also their costs could increase adoption rates because farmers get an honest and unbiased picture on requirements and consequences. This is of specific interest for the SI measures with lower adoption rates identified in Chapter 3. Education and demonstration projects may influence participation rates as they help showcasing the benefits of a measure to farmers. Such projects could show that the impact on economic output might be lower than expected or could be reduced by appropriately implementing the measure (cf. Vanslembrouck *et al.*, 2002 for AES). Experienced benefits are an important explanatory factor for the use of SI measures identified in the explorative path models of Chapter 3. If the portfolio and feedback effects through experience are confirmed in future research, the case for demonstration projects and exchange formats between farmers will be even stronger as additional measure uptake could be triggered.

Communication strategies can also be used to raise public interest in ecological themes and knowledge on farming to provide a positive feedback when farmers provide the requested benefits (Lemken *et al.*, 2017). This can be done through governmental action, for instance the 'International Year of Soils' proclaimed by the United Nations (UN, 2013), or driven by civil society, for instance the referendum on biodiversity in the German federal state Bavaria (Bündnis Artenvielfalt Bayern, 2019).

Farmers are known to act environmentally-friendly also beyond policy support schemes following intrinsic motivations (Thomas *et al.*, 2019). The results of Chapter 4 show that current AES neither guarantee the uptake of SI measure nor the use of the full environmental improvement potential. Hence, additional communication approaches are worth to be considered with the aim to improve SI outcomes. Communication strategies might foster entrepreneurial and pro-environmental attitudes of farmers and in turn voluntary pro-environmental action (Michel-Guillou and Moser, 2006). One could capitalize especially on the knowledge and experience of the early adopters of SI measures to demonstrate effects in terms of peer-to-peer learning. In a discrete choice experiment for perennial crops, Gillich *et al.* (2019) show that farmers' propensity to adopt increases if colleagues are already applying the practice. Kuhfuss *et al.* (2016) show that farmers decide subject to their information about social norms and are more likely to correspond to pro-environmental behaviour if they know about other farmers' environmental practices. This is referred to as conditional cooperation in game theory and experimental economics (Fischbacher *et al.*, 2001). However, if regional adoption rates are low, economic incentives may become more relevant (Dessart *et al.*, 2019).

3) Multi-stakeholder participatory governance

Result-based schemes and awareness raising campaigns acknowledge the role of the farmer. As decision-maker and producer of environmental goods farmers have substantial knowledge and experience to provide. However, both are top-down approaches and farmers are not included in the policy design and regional priority setting of measures and outcomes. Participatory governance approaches go one step further by inducing a bottom-up approach to policy-making. Farmers and land managers have been included in the design of AES as well as in the definition of payment levels (cf. Mettepenningen *et al.*, 2013). Beyond policy schemes, Lindblom *et al.* (2017) investigates a successful case where farmers are included in the development phase of a decision support tool and thus more likely to use it later on.

The stakeholder processes presented in Chapter 2 revealed that farmers and land managers have a clear vision on how their region could develop land-use sustainability at a landscape scale and which SI measures are relevant. Different groups of stakeholders, such as farmers and environmental protectionists, may develop a common goal setting through mutual dialogue. Participatory governance approaches moreover would take the claim of SI to be based on regional knowledge seriously (Pretty, 1997a; Franks, 2014). Prager (2015) explains that participatory governance approaches lead to increased acceptance and implementation of measures as well as to improved outcomes. Reasons for this higher identification are reflected in the generated social capital, trust, common norms, reciprocity and exchange (Appelstrand, 2012). However, one challenge in the practical application of participatory governance schemes could be rooted in high transaction costs to initiate and execute these processes which have to be weighed against the expected outcomes. Thus policymakers might consider to reserve such approaches for regions in which the environment is either extremely degraded or the expected benefits are high.

5.4 Future research directions

Each of the empirical studies presented in this dissertation only considers partial aspects of the relationships of sustainable intensification measures, farmers' adoption behaviour and environmental outcomes. While discussing the limitations of the three studies, we point out promising areas and approaches for future research.

1) Longitudinal data

The cross-sectional farm survey data used in chapters 3 and 4 limits the scope of answers provided to the research questions due to the lacking longitudinal character. SI is often considered from a process perspective of inducing dynamic improvements in agricultural systems over a certain time horizon (e.g., Firbank *et al.*, 2013). Thus we cannot assess whether or not the partially observed low within-technology performance of SI adopters (cf. Chapter 4) is caused by temporal inefficiencies related to adjustment costs and vanishes in the long-run as found by Ang and Oude Lansink (2017). A replication of the study would also be an asset to validate farmers' intentions to use further SI measures as a proxy for future behaviour as applied in the approach of Chapter 3. The extent to which farmers comply with their indicated planning allows assessing the predictive validity of studies based on behavioural intentions in agriculture. Additionally, the development of farmers' attitudes and norms could be tracked over time with longitudinal data. A future research direction is to evaluate whether these change with beneficial experiences of adopted SI measures as suggested by Yoder *et al.* (2019).

2) Data requirements and generalisability of results

The dataset lacks some desirable details. In order to link the study on adoption behaviour in Chapter 3 to established theories such as the Reasoned Action Approach of Fishbein and Ajzen (2011) more detailed questions on behavioural beliefs of farmers are necessary. Future studies could then give more evidence on the interrelationships of adoption decisions and farmers’ values and attitudes.

A trade-off between the degree of detail and the number of observations concerns the biodiversity indicator used to measure environmental outcomes in Chapter 4. The study uses proxy indicators and does not directly measure on-farm environmental outcomes. The latter might be an area of cooperation between ecologists and economists to identify valid proxy indicators for environmental outcomes that can be collected through large scale farm surveys. Although the number of available indicators for environmental sustainability has been steadily increasing (Latruffe *et al.*, 2016), consensus on a core set of indicators has not been reached yet. Suggestions have been made to enlarge established European datasets with biodiversity indicators to reach coherence of indicators across Europe, for instance by Kelly *et al.* (2018) for the FADN data set or Uthes *et al.* (2020) for the IACS data set.

Coherent data sets would also support comparative studies in other regions. While the procedure of analysis presented with the three empirical studies is transferable to other contexts, the degree of generalisability of results is difficult to estimate. Typology approaches reveal comparable regional and farm types across European regions (e.g., Weingarten *et al.*, 2010; Weltin *et al.*, 2017). Although the SI measures will vary regionally, demonstrated in Chapter 2 for three additional European case study areas, behavioural rationales and outcomes could be comparable for the same farm type and SI measures with similar characteristics. Further evidence would be helpful to suggest policy actions that can be transferred between regions with similar characteristics and agricultural systems. In the light of the post-2020 CAP, for which member states have the responsibility to design regionally adjusted policy measures in a ‘CAP strategic plan’ (European Commission, 2019), regionalised information becomes even more essential.

3) Barriers to adoption and unused improvement potential of SI measures

Chapter 3 shows that adoption rates for some SI measures are still limited. Chapter 4 points to eco-inefficiencies of SI adopters and unused potential for environmental improvement. Therefore, the assessment of remedies, support to farmers and other means to reduce barriers in the use of SI measures is an important field of future research. This might include but is not limited to the role of extension services in knowledge provision and advice (Kassam *et al.*, 2011), or the role of social learning and exchange of experience with peers (Läpple and Kelley, 2015). Social norms (Nyborg *et al.*, 2016) and pressure exerted by farmers' social referents (Mills *et al.*, 2017) are aspects that needs to be assessed in more detail than in this dissertation on their relevance for SI uptake and reduction of improvement potentials. The influence of groups of social referents such as family members (Burton and Wilson, 2006), other farmers (Kuhfuss *et al.*, 2016), or professional advisors (Blackstock *et al.*, 2010) needs to be differentiated. Dessart *et al.* (2019) have shown that the level of adoption depends on the share of surrounding adopters. Dedeurwaerdere *et al.* (2015) refer to so-called network bridging organisations that are non-state actors who facilitate and coordinate knowledge exchange between different stakeholder groups in a region and encourage social learning. In the example of the Rhinluch region, this role could be filled by the Water and Soil Association, which farmers consider trustworthy for supporting coordination between neighbouring farms, e.g. with regard to AES (Häfner *et al.*, 2017). Although such approaches are cost and time intensive, they may yield higher commitment to change and effective implementation of SI measures. Regarding the interrelations in decision-making, the identification of regional trigger measures that foster the use of additional SI measures would be of interest to get farms to gradually broaden their portfolios of SI measures.

4) The role of timing in joint decision-making

Temporal aspects are an issue for further research not only in terms of data. Two points about timing and decision-making require a closer look. First, the differences between farmers who already use SI measures and those that plan implementation at a later stage are of interest in terms of adoption behaviour (cf. Chapter 3). Moreover, these differences may also influence the effectiveness of using SI measures and the size of potential short-term eco-inefficiencies. Thus characterising different groups of farmers with respect to the timing of adoption and their needs would reveal more details on relevant factors fostering SI implementation and effective use. The second aspect relates to a potential feedback effect from the applied measures on the norms and attitudes of farmers raised by Yoder *et al.* (2019). Changes in norms and attitudes in turn could trigger further adoption. Breaking the endogeneity between attitudes and norms shaping adoption and outcomes and vice versa would be an interesting realm of methodological approaches in causal effect studies.

5) SI measures beyond the farm scale

Empirically this dissertation mainly addresses SI measures on the farm level for which the farmer acts as the single decision-maker. As a basis to analyse the relevance of agents' behaviour for SI application and environmental outcomes, starting with the rationales of a single decision-maker is necessary. However, SI measures beyond the farm level at a regional or landscape scale showed a high relevance for regional stakeholders (cf. Chapter 2). In this case, several persons are involved in a coordinated or collaborative decision-making process. Examples are land sharing approaches with landscape elements planned on a landscape scale to prevent habitat fragmentation and increase species diversity (cf. Smith *et al.*, 2019) or resource exchange across different farms in a region to close resource cycles. Studying these decisions and interactions of farmers and other stakeholder is relevant to understand the full impact of SI measures. The complexity of analysing such cooperative decisions has already been acknowledged (e.g., Westerink *et al.*, 2017). Determinants for the success of collaboration and coordination on the landscape scale would thus be of interest beyond the research of SI, e.g. for collaborative AES (cf. Prager, 2015).

5.5 Concluding remarks

Sustainable intensification is a topic that concerns multiple disciplines, such as agricultural and biological sciences, environmental sciences, social sciences and economics, and has a strong practical and political relevance. Thus, we close this dissertation with the core contributions for a disciplinary audience in agricultural economics as well as for the multidisciplinary discourse on sustainable intensification.

With regard to the interdisciplinary SI literature, the dissertation offers an overview and conceptual categorisation of SI measures across disciplines. Additionally, we highlight the important role of decision-makers, in this case farmers, who influence the uptake and goal attainment of SI measures in terms of environmental benefits. We underscore that the decision-makers’ perspectives need to be considered when analysing the targets and outcomes of SI measures.

For the literature on adoption behaviour in agricultural economics, we highlight the necessity to consider the joint adoption of sustainable farming practices to understand decision rationales. The insights go beyond the case of SI measures and suggest how existing theories and methods to study adoption behaviour could be enhanced when the decision process is complex and feedback effects among decisions exist. This may also apply to studies on digitisation of the farm business, income diversification or conservation agriculture, for instance.

For the literature on eco-efficiency analysis in agricultural economics, we provide further guidance on how differences in eco-efficiency scores between groups of farms, for instance with different production systems, can be causally interpreted to reflect specific goals, such as environmental improvement. Therefore, we combine a directional non-parametric meta-frontier approach and matching. This approach could be relevant to evaluate the outcomes of farm-level interventions beyond SI measures.

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Appendices

Appendix A: Details on the systematic literature review of Chapter 2[13]

Specification table

Subject area	*Agricultural and Biological Sciences*
More specific subject area	*Sustainable intensification*
Type of data	*Table (Excel)*
How data was acquired	*Systematic search in Scopus and Web of Science databases*
Data format	*Raw and analysed*
Experimental factors	*The term “Sustainable Intensification” was searched in title, abstract and author keywords of all articles and review papers until December 31, 2016.*
Experimental features	*Bibliographic information on the selected articles was recorded as well as the geographic area of the study and sustainable intensification practices it primarily investigates.*
Data source location	*Global data*
Data accessibility	*https://www.sciencedirect.com/science/article/pii/S2352340918306802*

Value of the data

- The data provides a comprehensive overview on the two complete decades of scientific literature on sustainable intensification, including information on internal and external referencing.
- Targeted selection and assessment of relevant literature depending on specific keywords, geographical regions or sustainable intensification practices of interest is facilitated.
- The data builds a baseline for comparative as well as in-depth analyses of sustainable intensification implementation.
- Background information for studies of different disciplines related to sustainable intensification is summarized.

[13] This Appendix is based on the following publication: Weltin, M., Zasada, I., Plogmann, J. M., Trau, F. N., & Piorr, A. (2018). Data on the scope of the literature on sustainable intensification 1997–2016: Bibliography, geography and practical approaches. *Data in Brief*, *19*, 1658-1660.

Data

The dataset provided allows a comprehensive overview of the relevant scientific literature in the field of sustainable intensification (SI) research. Sustainable intensification is the umbrella term of a scientific discussion that seeks ways to ensure food production at less environmental cost (Baulcombe *et al.*, 2009; Pretty and Bharucha, 2014). The number of included articles in the dataset is 349 covering the years 1997 to 2016. For each article bibliographic information is provided, such as authorship, title, year of publication, journal, author keywords, number of citations within and outside the analysed body of literature, and references. The geographic area(s) the article focuses on is additionally included, differencing world regions. The dataset further contains information on which of 26 identified SI approaches a publication mainly refers to.

Experimental Design, Materials and Methods

The Scopus (https://www.scopus.com/) and the Web of Science (https://apps.webofknowledge.com/) databases were used to collect relevant articles. They represent the two main collections of academic literature (Aghaei Chadegani *et al.*, 2013). For that purpose, the term "Sustainable Intensification" was searched for in title, abstract and author keywords of research articles and review papers. The final database consists of 349 articles representing all published articles up to December 31st, 2016. The overlap of the two databases is 271 articles. 59 are available in the Scopus database exclusively, 19 in the Web of Science respectively. Available bibliographic information of each article provided was retrieved. Citation records were retrieved from Scopus. The Web of Science was only used for the 19 articles exclusively registered there. Regarding citations, the number of citations of any given article by the other selected papers was tallied, representing the internal relevance of the article. Due to data formats, this was only done for the 330 articles originating from Scopus. The geographic focus area was extracted from the title or abstract of the paper.

The most important sustainable intensification practices were identified by evaluating the abstracts and conclusions of the articles. Following the approach by Gao *et al.* (2017) an iterative multidisciplinary expert evaluation including economics, geography, natural resource management, agricultural sciences was applied to identify similar practices in order to cluster them into consistent bundles of practices forming SI approaches. Finally, 26 SI approaches were specified, to which the papers were assigned accordingly. Detailed information concerning the practices represented in approach is included in the metadata file of the provided dataset.

Appendix B: Survey questionnaire

Part B of the questionnaire was not used for this dissertation except to calculate the farms' peatland area. The full questionnaire in English translation is available in Weltin *et al.* (2019).

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FRAGEBOGEN – TEIL A

Vielen Dank, dass Sie sich bereit erklären, diesen Fragebogen auszufüllen.

Wir bitten um die Beantwortung des Fragebogens durch einen Betriebsleiter oder einen leitenden Angestellten.

Wenn Sie Flächen auf Moorböden oder ehemaligen Moorböden haben, möchten wir Sie bitten zusätzlich zu diesem Teil noch einige wenige **zusätzliche Fragen in Teil B** zu beantworten.
Alle Angaben sind freiwillig.

A. Allgemeine Angaben zum Betrieb und der Bewirtschaftung

1 ▸ Welche Rechtsform hat Ihr landwirtschaftlicher Betrieb?

- ☐ Einzelunternehmen
- ☐ Juristische Person (z.B. eG, GmbH, AG)
- ☐ Personengesellschaft (z.B. GbR)
- ☐ andere, und zwar ____________

2 ▸ Ist ein Betriebsleiter Eigentümer des Betriebes?

- ☐ Ja
- ☐ Nein

3 ▸ Welchen Erwerbscharakter hat Ihr Betrieb?

- ☐ Haupterwerbsbetrieb
- ☐ Nebenerwerbsbetrieb

4 ▸ Wie lautet die Postleitzahl des Betriebssitzes?

PLZ ____________

5 ▸ Wie viel landwirtschaftliche Fläche bewirtschaftet Ihr Betrieb?

Ackerland ____________ **ha**

Grünland ____________ **ha** davon sind ____________ **ha** Dauergrünland

6 ▸ Wie ist die Standortgüte Ihrer Flächen?

Ackerzahlen: kleinster Wert ____________ Durchschnittswert ____________ größter Wert ____________

Grünlandzahlen: kleinster Wert ____________ Durchschnittswert ____________ größter Wert ____________

7 ▸ Wie viel der landwirtschaftlichen Fläche haben Sie gepachtet?

Insgesamt ca. ____________ **ha** Pachtfläche

8 ▸ Auf wie viel Ihrer landwirtschaftlichen Fläche treffen folgende Beschreibungen zu…?

a) Flächen in benachteiligten Gebieten: insgesamt ____________ **ha**

b) Flächen mit Naturschutzauflagen: insgesamt ____________ **ha**

9 ▸ Welche Ausrichtung hat ihr Betrieb?

- ☐ spezialisiert auf Futterbau (Weidevieh und Futterbau > 2/3)
- ☐ spezialisiert auf Ackerbau (Ackerbau > 2/3)
- ☐ Verbundbetrieb/ Gemischtbetrieb
- ☐ andere, und zwar ____________

10 ▸ Ackerbau: Wie viele verschiedene Feldfrüchte haben Sie im letzten Jahr auf Ihrem Betrieb angebaut?

Anzahl ____________

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11 ▸ Ackerbau: Welche drei Feldfrüchte haben den größten Anbauumfang und wie waren deren durchschnittlichen Erträge in den letzten 5 Jahren?

	Frucht	Durchschnittlicher Ertrag in den letzten 5 Jahren (**dt/ha**)
1		
2		
3		

12 ▸ Grünland: Wie nutzen Sie das Grünland auf Ihrem Betrieb?

☐ ausschließlich Beweidung ☐ ausschließlich Mahdnutzung ☐ Beweidung und Mahdnutzung

bei Mahd: durchschnittlicher Ertrag in den letzten 5 Jahren ____________ **dt/ha**

13 ▸ Tierhaltung: Wie setzt sich ihr Viehbestand aktuell zusammen?

Milchvieh (einschließlich Nachzucht) (Anzahl) ________ Fleischrinder (einschließlich Kälber) ____________

Schweine (Anzahl) ____________ Schafe oder Ziegen (Anzahl) ____________

Geflügel (Anzahl) ____________ Andere, und zwar: ____________

14 ▸ Bewirtschaften Sie Ihren Betrieb konventionell, ökologisch oder befinden Sie sich in der Umstellung?

☐ konventionell (immer gewesen) ☐ konventionell (rückumgestellt)

☐ ökologisch (in Umstellung) ☐ ökologisch, seit ________ Jahren

15 ▸ Wie viele Arbeitskräfte (einschließlich Ihnen) hat Ihr Betrieb derzeit?

Mitarbeitende Familienarbeitskräfte (Anzahl) ________ Vollzeitangestellte (Anzahl) ____________

Teilzeitangestellte (Anzahl) ____________ Saisonarbeitskräfte im letzten Jahr (Anzahl) ________

16 ▸ Wie hat sich Ihre Nährstoffbilanz (Feld-Stall-Bilanz) entwickelt?

Benennen Sie dafür die Bilanz des letzten Jahres und folgende Durchschnittswerte.

Stickstoffbilanz: Letztes Düngejahr ________ **kg/ha** Drei-Jahres Durchschnitt ________ **kg/ha**

Phosphatbilanz: Letztes Düngejahr ________ **kg/ha** Sechs-Jahres Durchschnitt ________ **kg/ha**

17 ▸ Wie hat sich Ihr Einsatz von Betriebsmitteln entwickelt?

	Im letzten Jahr	**Durchschnittliche Entwicklung in den letzten 5 Jahren**: Zunahme	gleich geblieben	Abnahme
a) Mineralische Düngemittel	kg/ha	☐	☐	☐
b) Pflanzenschutzmittel	l/ha	☐	☐	☐

☐ keine Angabe

18 ▸ Werden auf Ihrem Betrieb Greening-Maßnahmen durchgeführt?

☐ Ja, und zwar auf insgesamt ________ **ha** ☐ Nein ☐ Der Betrieb ist befreit.

19 ▸ Werden oder wurden auf Ihrem Betrieb freiwillige Agrarumweltmaßnahmen durchgeführt?

Vor 2013: ☐ Ja ☐ Nein

Aktuell: ☐ Ja, und zwar auf ____________ **ha** ☐ Nein

Wenn aktuell ja, es werden folgende Maßnahmen durchgeführt:

☐ Nachhaltige Verfahren im Ackerbau
☐ Strukturelemente auf Ackerland
☐ Vielfältige Kulturen im Ackerbau
☐ Gewässerschonende Düngung
☐ Extensive Bewirtschaftung von Grünland
☐ Weidehaltung
☐ Ökologischer Landbau
☐ Andere, und zwar ______________________________

B. Betriebliche Entwicklungen

Einige Fragen beziehen sich auf den Zeitraum der letzten 5 Jahre. Sollte Ihr Betrieb jünger als 5 Jahre sein beziehen Sie Ihre Antwort auf den Zeitraum seit Bestehen des Betriebs.

20 ▸ Erfolgten in den letzten 5 Jahren wesentliche Veränderungen in der Struktur Ihres Betriebes, bzw. sind in den nächsten 5 Jahren Veränderungen beabsichtigt?

	In den letzten 5 Jahren	In den nächsten 5 Jahren beabsichtigt
a) Landwirtschaftliche Fläche	☐ Vergrößerung ☐ Verkleinerung ☐ keine Veränderung	☐ Vergrößerung ☐ Verkleinerung ☐ keine Veränderung ☐ weiß ich noch nicht
b) Tierbestand	☐ Vergrößerung ☐ Verkleinerung ☐ keine Veränderung	☐ Vergrößerung ☐ Verkleinerung ☐ keine Veränderung ☐ weiß ich noch nicht
c) Betriebsmitteleinsatz	☐ Intensivierung ☐ Extensivierung ☐ keine Veränderung	☐ Intensivierung ☐ Extensivierung ☐ keine Veränderung ☐ weiß ich noch nicht
d) Arbeitskräfteeinsatz	☐ Aufstockung ☐ Abbau ☐ keine Veränderung	☐ Aufstockung ☐ Abbau ☐ keine Veränderung ☐ weiß ich noch nicht
e) Agrarumweltmaßnahmen	☐ Ausweitung ☐ Reduzierung ☐ keine Veränderung	☐ Ausweitung ☐ Reduzierung ☐ keine Veränderung ☐ weiß ich noch nicht
f) Investitionen in Maschinen und Ausrüstung	☐ Investitionen erfolgt ☐ keine Investitionen erfolgt	☐ Investitionen beabsichtigt ☐ keine Investitionen beabsichtigt ☐ weiß ich noch nicht

Folgende Maßnahmen werden im Rahmen einer besseren Vereinbarkeit von betriebswirtschaftlichem Erfolg und Schutz von Natur und Umwelt in Wissenschaft und Agrarpolitik als zukünftig wichtig und unterstützenswert diskutiert. Sie können helfen, die aus der Sicht der Praxis wichtigen zu benennen.

21a ► **Welche dieser Maßnahmen wenden Sie aktuell auf Ihrem Betrieb an oder planen Sie in der näheren Zukunft anzuwenden?**

21b ► **Welche Effekte hatten Sie nach Anwendung der Maßnahme?** (mehrere Antworten möglich)

21c ► Welche **drei Maßnahmen** sind Ihrer Meinung nach **am wichtigsten** für eine bessere Vereinbarkeit von betriebswirtschaftlichem Erfolg **und** Schutz von Natur und Umwelt?

	21a: Nein	21a: Ist geplant	21a: Ja, wende ich an und erhalte Förderung dafür	21a: Ja, wende ich an ohne Förderung	21b: Gewinnsteigerung	21b: Ertragssteigerung	21b: Betriebsmitteleinsparung	21b: positive Umweltauswirkungen	21b: keine der genannten	21c: Kreuzen Sie bis zu drei Maßnahmen an
1. Reduzierte/ Konservierende Bodenbearbeitung auf Grünland	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2. Reduzierte/ Konservierende Bodenbearbeitung auf Ackerland	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3. Zwischenfruchtbau (einschließlich Untersaaten)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4. Anbau von Leguminosen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5. Anbau von mindestens 5 Kulturen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6. Blüh- oder Schonstreifen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7. Brache	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8. Weidehaltung	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9. Precision Farming, teilflächenspezifische Bewirtschaftung	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10. Verwendung von Produktionsresten oder Nebenprodukten als Tierfutter	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11. Integrierter Pflanzenschutz	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12. Nutzung von kommerzieller Agrar- oder Betriebsmanagementsoftware	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13. Bewirtschaftung von Flächen mit Vertragsnaturschutzauflagen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14. Austausch von Betriebsmitteln (z.B. Wirtschaftsdünger, Biomasse) mit anderen Betrieben in der Region	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
15. Mitgliedschaft in Maschinenringen, Erzeugergemeinschaften oder Kooperativen	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
16. Direktvermarktung landwirtschaftlicher Erzeugnisse	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
17. Vermarktung unter Regionalmarken	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
18. Absprachen und Kooperation mit verschiedenen Interessensgruppen der Landnutzung in der Region	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
19. Andere, und zwar:	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Keine dieser Maßnahmen ist geeignet ☐

22 ▸ Wie oft oder selten…

	sehr oft	oft	gelegentlich	selten	nie
a) … holen Sie sich einen Rat bei **anderen Landwirten**?	☐	☐	☐	☐	☐
b) … stimmen Sie sich für betriebliche Entscheidungen **mit benachbarten landwirtschaftlichen Betrieben** ab?	☐	☐	☐	☐	☐
c) … holen Sie sich einen Rat bei einer **landwirtschaftlichen Fachberatung**?	☐	☐	☐	☐	☐

23 ▸ Wie wichtig oder unwichtig sind Städte für Sie hinsichtlich folgender Aspekte?

	sehr wichtig	eher wichtig	weder wichtig noch unwichtig	eher unwichtig	sehr unwichtig	**Bitte tragen Sie den Namen der dafür wichtigsten Stadt hier ein.**
a) Absatz landwirtschaftlicher Erzeugnisse	☐	☐	☐	☐	☐	
b) Absatz nicht-landwirtschaftlicher Produkte und Dienstleistungen	☐	☐	☐	☐	☐	
c) Zugang zu nötigem Wissen und Beratung	☐	☐	☐	☐	☐	
d) Absprachen und Kooperation mit Vertretern der Landnutzung	☐	☐	☐	☐	☐	
e) als Lebensmittelpunkt und für soziale Kontakte	☐	☐	☐	☐	☐	

24 ▸ Wer sind die Abnehmer Ihrer landwirtschaftlichen Erzeugnisse? (mehrere Antworten sind möglich)

☐ Supermärkte ☐ Spezialitätenläden ☐ Hofläden

☐ Kooperativen ☐ Großhändler ☐ andere, und zwar ____________________

25 ▸ Sind Sie oder eines Ihrer Haushaltsmitglieder Mitglied in Verbänden oder Organisationen?
(mehrere Antworten sind möglich)

☐ Bauernverband oder andere landwirtschaftliche Verbände

☐ politische Partei und/oder Kommunalverwaltung

☐ Umwelt-/Naturschutzorganisation oder Landschaftspflegeverband

☐ andere, und zwar ____

☐ keine

☐ keine Angaben

26▶ Treffen folgende Aussagen auf Sie zu oder nicht?

Bitte nutzen Sie die 10-Punkte-Skala von (1) trifft gar nicht zu bis (10) trifft vollständig zu.

	1 (trifft gar nicht zu)	2	3	4	5	6	7	8	9	10 (trifft vollständig zu)
a) Ich fühle mich sehr mit der Region verbunden, in der ich wirtschafte.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
b) Als Landwirt habe ich eine besondere Verantwortung als Arbeitgeber und für die wirtschaftliche Entwicklung in meiner Region.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
c) Ich gehöre normalerweise zu den ersten in meiner Region, die neue Verfahren auf dem Betrieb anwenden.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
d) Die Zusammenarbeit mit anderen Landwirten in der Region ist für mich wichtig.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
e) Die Zusammenarbeit mit Vertretern aus Wirtschaft und Gesellschaft in der Region ist für mich wichtig.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
f) Die naturräumlichen Bedingungen an meinem Standort (z.B. Bodenbeschaffenheit) sind günstig für die Landwirtschaft.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
g) Als Landwirt sehe ich mich vor allem als Produzent; Aufgaben in Umweltschutz, Landschaftspflege sind für mich zweitrangig.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
h) Bei betrieblichen Entscheidungen bin ich bereit Risiken einzugehen.	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

E. Informationen zu Ihrem Haushalt und zur Betriebsleitung

27▶ Wann haben Sie die Leitung des Betriebs übernommen?

Im Jahr __________

28▶ Auf wie viele Jahre landwirtschaftliche Praxis blicken Sie zurück?

Insgesamt __________ Jahre

29▶ Ist die Nachfolge für den Betrieb bereits geregelt oder nicht?

☐ Ja, Nachfolge ist gesichert. ☐ Nein, noch nicht geregelt. ☐ Nein, Betrieb wird aufgegeben.

30▶ Welches ist Ihr höchster allgemeiner Bildungsabschluss?

☐ Kein Abschluss
☐ Volks-/Hauptschulabschluss (DDR: 8.Klasse)
☐ Mittlere Reife, Realschulabschluss (DDR: 10. Klasse)
☐ Abitur, Hochschulreife (DDR: EOS), Fachhochschulreife
☐ Universitäts- oder Fachhochschul-Abschluss

31▶ Haben Sie eine formale landwirtschaftliche Ausbildung?

☐ Ja ☐ Nein

32▶ In welchem Jahr sind Sie geboren?

Im Jahr __________

33▶ Welches Geschlecht haben Sie?

☐ Weiblich ☐ Männlich

34▶ Leben die Mitglieder Ihres Haushalts auf dem landwirtschaftlichen Betrieb?

☐ Ja ☐ Nein

35 ▶ Wie viele Personen leben aktuell in Ihrem Haushalt, einschließlich Ihnen selbst?

__________ Personen (Anzahl) davon sind (Anzahl) __________ jünger als 18 Jahre

und (Anzahl) __________ älter als 65 Jahre

36 ▶ Haben Sie neben der landwirtschaftlichen Produktion noch Einkommen aus anderen Aktivitäten auf dem Betrieb (z.B. durch Fremdenverkehr, Direktvermarktung, …)?

☐ Ja ▶ Wenn ja, welchen **Anteil** machen diese Einkünfte **am Haushaltseinkommen** aus?

☐ bis 25% ☐ über 25% bis 50% ☐ über 50% bis 75% ☐ mehr als 75%

☐ Nein

37 ▶ Gehen Mitglieder Ihres Haushalts (einschließlich Ihnen selbst) einer Arbeit außerhalb des eigenen landwirtschaftlichen Unternehmens nach?

☐ Ja ▶ Wenn ja, nennen Sie bitte

a) Mitglieder in Vollzeit (Anzahl) __________

b) Mitglieder in Teilzeit (Anzahl) __________ für zusammengezählt __________ Stunden/Woche

c) **Anteil** aller Einkünfte aus außerbetrieblicher Arbeit **am Haushaltseinkommen:**

☐ bis 25% ☐ über 25% bis 50% ☐ über 50% bis 75% ☐ mehr als 75%

☐ Nein

38 ▶ Wie hoch war der Betriebsgewinn im letzten Wirtschaftsjahr?

☐ Verlust/kleiner Null €	☐ bis 10.000€	☐ bis 20.000€	☐ bis 40.000€
☐ bis 60.000€	☐ bis 80.000€	☐ bis 100.000€	☐ bis 120.000€
☐ bis 140.000€	☐ bis 200.000€	☐ bis 250.000€	☐ mehr als 250.000€

39 ▶ Wie war die Gewinnentwicklung innerhalb der letzten 5 Jahre?

☐ Zunahme um mehr als 20% ☐ Zunahme um 5% bis 20%

☐ Zwischen Zunahme um 5% und Abnahme um 5%

☐ Abnahme um 5% bis 20% ☐ Abnahme um mehr als 20%

☐ keine Angabe

Wir bedanken uns sehr herzlich bei Ihnen, dass Sie sich die Zeit genommen haben unseren Fragebogen zu beantworten.

Haben Sie noch Anregungen oder Kommentare zum Fragebogen für uns?

Appendix C: Additional results of Chapter 3

Table C.1 Full estimation results multivariate probit model

	SI_agro	SI_past	SI_tech	SI_land	SI_mark
Land [log ha]	0.57	0.14	0.33	0.33	-0.02
	(0.00)	(0.10)	(0.00)	(0.00)	(0.83)
Organic farm [1=yes, 0=no]	-0.17	0.16	-0.40	-0.61	0.51
	(0.47)	(0.40)	(0.10)	(0.00)	(0.01)
Specialised in arable farming [1=yes, 0=no]	0.58	-1.48	0.31	0.78	-0.06
	(0.02)	(0.00)	(0.09)	(0.00)	(0.74)
Full-time farm [1=yes, 0=no]	-0.17	0.03	-0.16	-0.13	0.19
	(0.53)	(0.89)	(0.57)	(0.60)	(0.47)
Labour intensity [workforce/ UAA]	2.10	0.29	3.32	2.05	2.55
	(0.17)	(0.81)	(0.03)	(0.14)	(0.15)
Frequency of using extension services [5 categories]	0.05	-0.14	0.17	0.01	0.12
	(0.55)	(0.06)	(0.03)	(0.93)	(0.11)
Highest educational degree [3 categories]	0.38	-0.15	0.06	0.06	0.16
	(0.00)	(0.10)	(0.55)	(0.52)	(0.11)
Farming experience [years]	0.00	0.01	-0.02	-0.01	0.01
	(0.95)	(0.08)	(0.01)	(0.29)	(0.04)
Share of adoption in postal code area	5.29	2.29	2.83	2.85	3.48
	(0.00	(0.00)	(0.00)	(0.00)	(0.00)
Constant	-6.52	-0.98	-3.37	-3.04	-2.98
	(0.00)	(0.09)	(0.00)	(0.00)	(0.00)
SI_agro		0.16	0.41	0.64	0.35
		(0.21)	(0.02)	(0.00)	(0.01)
SI_past	0.16		0.09	-0.22	0.08
	(0.21)		(0.45)	(0.03)	(0.45)
SI_tech	0.41	0.09		0.20	0.33
	(0.02)	(0.45)		(0.09)	(0.01)
SI_land	0.64	-0.22	0.20		0.32
	(0.00)	(0.03)	(0.09)		(0.00)
SI_mark	0.35	0.08	0.33	0.32	
	(0.01)	(0.45)	(0.01)	(0.00)	

Source: Own representation based on farm survey data.

Table C.2 Composite reliability (CR) and average variance extracted (AVE)

	Landscape elements		Technological SI		Regional marketing	
	CR	AVE	CR	AVE	CR	AVE
Env. sustainability attitude	1.00	1.00	1.00	1.00	1.00	1.00
Econ. sustainability attitude	0.83	0.61	0.81	0.60	0.84	0.64
Social interaction values	0.82	0.60	0.81	0.59	0.74	0.59
Social interaction activities	0.84	0.72	0.85	0.73	1.00	1.00
Experienced benefits	0.76	0.53	0.80	0.49	0.79	0.50
Other future plans	1.00	1.00	1.00	1.00	1.00	1.00

Source: Own representation based on farm survey data.

Table C.3 Heterotrait-Monotrait Ratio for technological SI measures

	(1)	(2)	(3)	(4)	(5)	(6)
(1) Experienced benefits						
(2) Economic sustainability attitude	0.64					
(3) Environmental sustainability attitude	0.08	0.09				
(4) Intention to adopt	0.30	0.28	0.03			
(5) Other future plans	0.22	0.04	0.01	0.20		
(6) Social interaction activities	0.29	0.42	0.06	0.16	0.10	
(7) Social interaction values	0.54	0.90	0.15	0.20	0.14	0.56

Source: Own representation based on farm survey data.

Table C.4 Heterotrait-Monotrait Ratio for landscape elements

	(1)	(2)	(3)	(4)	(5)	(6)
(1) Experienced benefits						
(2) Economic sustainability attitude	0.50					
(3) Environmental sustainability attitude	0.12	0.22				
(4) Intention to adopt	0.40	0.17	0.18			
(5) Other future plans	0.13	0.27	0.03	0.23		
(6) Social interaction activities	0.37	0.51	0.05	0.21	0.13	
(7) Social interaction values	0.42	0.95	0.11	0.09	0.13	0.51

Source: Own representation based on farm survey data.

Table C.5 Heterotrait-Monotrait Ratio for regional marketing

	(1)	(2)	(3)	(4)	(5)	(6)
(1) Experienced benefits						
(2) Economic sustainability attitude	0.46					
(3) Environmental sustainability attitude	0.05	0.10				
(4) Intention to adopt	0.18	0.13	0.15			
(5) Other future plans	0.17	0.09	0.07	0.11		
(6) Social interaction activities	0.11	0.22	0.10	0.05	0.08	
(7) Social interaction values	0.57	1.18	0.20	0.04	0.17	0.49

Source: Own representation based on farm survey data.

Appendix D: Variable and sample generation for Chapter 4

Part I: Variable generation: results of the factor analysis on farmers' value statements

To obtain measures of farmers' values and attitudes, in the survey, farmers indicated their approval with the statements below.

Question: What do you think of the following statements? (cf. Weltin *et al.*, 2019 or Appendix B question 26)

Please express your approval by using the 10-point-scale from (1) no approval to (10) full approval.

1) I am very attached to the region I am farming in.
2) As farmer I have a special responsibility as employer and for the economic development of my region.
3) I am usually one of the first in my region to apply new procedures on my farm.
4) I consider myself, as a farmer, mostly as a producer; of secondary importance for me are duties regarding environmental protection or landscape maintenance. *(Remark: the variable is used in the analysis with a reversed scale to indicate environmental awareness.)*
5) Regarding operational decisions I like to take risks.

Principal component factor analysis revealed a three factor solution setting a minimum of 70% explained variance as a selection criterion and aiming for a simple structure. Factors were named according to the variables loading highly on them.

Table D. 1 Rotated factor loadings

Variable	Factor1: *Entrepreneurial attitude*[1]	Factor2: *Environmental awareness*	Factor3: *Regional attachment*
1) Regional attachment	0.03	0.00	**0.98**
2) Regional economic responsibility	**0.77**	0.09	0.27
3) Innovativeness	**0.84**	0.05	-0.07
4) Environmental awareness	-0.01	**0.97**	0.01
5) Propensity to take business risks	**0.74**	-0.29	-0.01

Note: N=364. Rotation method: orthogonal varimax. Explained variance=78.56%. Variables are assigned to the factor to which they have the highest loading indicated in grey.

[1] The final entrepreneurial attitude variable is calculated by the unweighted average of the three variables associated with factor 1.

Source: Own representation based on farm survey data.

Part II: Outlier control: details and results of minimum covariance determinant procedure

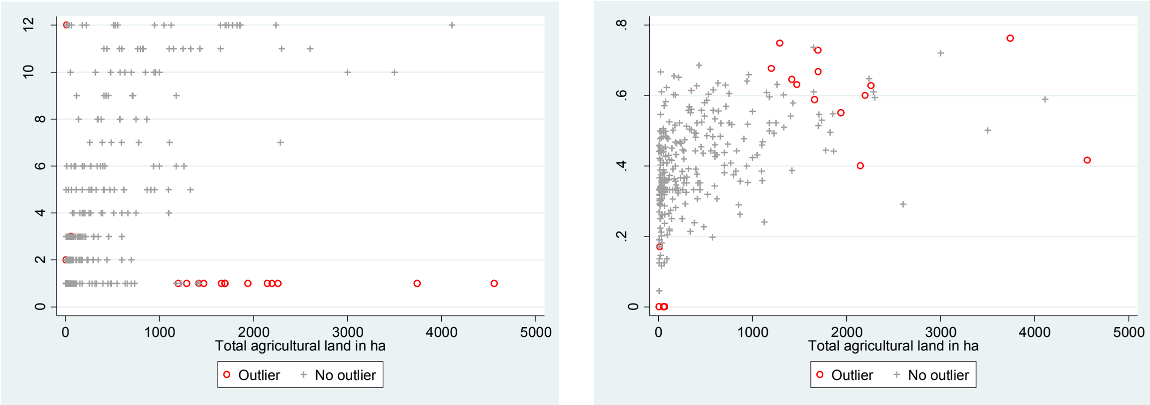
The outlier detection is based on the estimation of robust Mahalanobis distances: $d(\boldsymbol{x}, \hat{\mu}, \hat{\Sigma}) = \sqrt{(\boldsymbol{x} - \hat{\mu})' \,\widehat{\boldsymbol{\Sigma}}^{-\mathbf{1}}(\boldsymbol{x} - \hat{\mu})}$ where $\hat{\mu}$ and $\hat{\Sigma}$ consider only a subset h of the observations. In an iterative calculation, the minimum covariance determinant estimator selects the subset h_0 for which determinant of $\hat{\Sigma}$ is minimized with $\widehat{\mu_0}$ as mean and $\widehat{\Sigma_0}$ as the scaled covariance matrix of these h_0 observations. The procedure prevents that the estimated distances are influenced by outliers in the data (masking effect). The larger the robust distance, the further away an observation is situated from the centre of the data. Outliers are all observations above the cut-off value $\sqrt{\chi^2_{df;p}}$ where the degrees of freedom (df) are equal to the number of variables included in the analysis and p indicates a chosen significance level. For methodological details refer to Rousseeuw and Driessen (1999) and (Hubert *et al.*, 2018).

We checked the data for outliers considering the inputs and outputs used for data envelopment analysis which are the profit indicator, the environmental output indicator and land (df=3). For the cut-off value a significance level of p=0.01 is chosen.

Table D.2 Outputs and input for eco-efficiency analysis (before and after outlier control)

	Before outlier control		After outlier control[a]	
Variables	Mean	Std. Dev.	Mean	Std. Dev.
Economic output: profit indicator [1; 12]	4.21	3.65	4.33	3.66
Ecological output indicator [0;1]	0.41	0.13	0.40	0.12
Input: Used agricultural area [ha]	447.52	682.17	383.17	575.61
Sustainable intensification [1=yes; 0=no]	0.81	0.40	0.80	0.40
N	325		308	

[a]An outlier is identified by a robust Mahalanobis distance larger than the cut-off value $\mathrm{sqrt}(\chi^2_{3;0.01})$.
Source: Own representation based on farm survey data.



a) Profit indicator and land b) Ecological output indicator and land

Figure D.1 Outliers in the data.

Source: Own representation based on farm survey data.

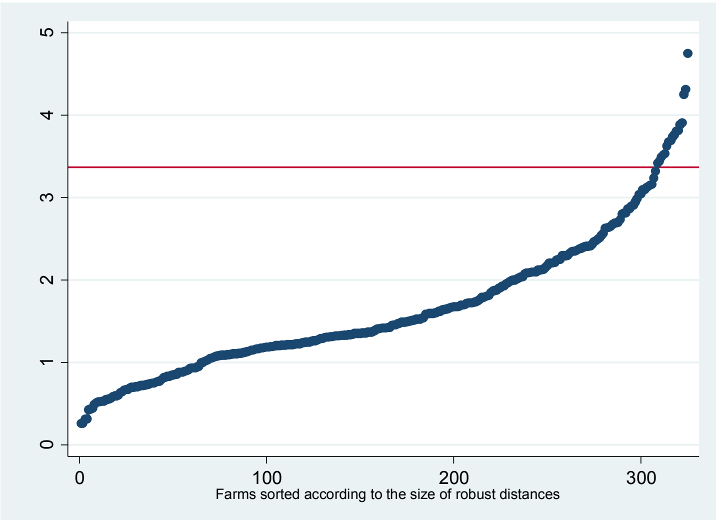


Figure D.2 Robust Mahalanobis distances and cut-off value.

Note: cut-off is defined as $\sqrt{\chi^2_{3;0.01}} = \mathbf{3.37}$ (red horizontal line).

Source: Own representation based on farm survey data.

Part III: Descriptive variables of the final sample used for analysis

Table D.3 Descriptive statistics of matching variables for the observations used in Data Envelopment Analysis

	SI farms		Non-SI farms	
Variables	Mean	Std. Dev	Mean	Std. Dev
Used agricultural area [ha]	489.99	631.19	108.27	174.94
Profit character [1=full-time; 0=part-time]	0.73	0.45	0.43	0.50
Organic farming [1=yes; 0=no]	0.21	0.41	0.25	0.44
Specialisation arable farming [1=yes; 0=no][a]	0.37	0.48	0.27	0.45
Labour intensity [workforce/ha UAA][b]	0.04	0.07	0.05	0.07
Use of extension services [1;5][c]	3.00	1.23	2.36	1.24
Formal agricultural education [1=yes; 0=no]	0.78	0.41	0.66	0.48
Highest educational degree [1; 3][d]	2.42	0.85	2.02	0.98
Farming experience [years]	26.82	12.62	28.00	14.35
Regional attachment [1; 10][e]	8.88	1.89	8.68	1.90
Environmental awareness [1; 10][e]	7.20	2.51	6.66	2.79
Entrepreneurial attitude [1; 10][e]	6.39	2.10	4.93	2.07
Economic output: profit indicator [1; 12]	5.05	3.79	2.70	2.37
Ecological output indicator [0; 1]	0.43	0.12	0.34	0.09
N	221		44	

[a] According to the self-assessment of the farmer.
[b] Workforce below 1 person is summarized as 1.
[c] 1=never; 2=sometimes; 3=occasionally; 4=often; 5=very often
[d] 1=lower secondary or intermediate education or no degree; 2=high school degree; 3=university degree
[e] Self-assessment questions for which respondents indicated the degree of agreement on a scale from 1=fully disagree to 0=fully agree
Source: Own representation based on farm survey data.

Appendix E: Additional results of Chapter 4

Part I: Matching results

Table E. 1 Means and standardised differences (std. diff.) of SI farms and non-SI farms before and after matching

	before matching			after matching				
				matched			unmatched	
	Mean SI=1	Mean SI=0	Std. diff.	Mean SI=1	Mean SI=0	Std. diff.	Mean SI=1	Mean SI=0
Profit character [1=full-time; 0=part-time]	0.73	0.43	0.63	0.76	0.70	0.13	0.50	0.33
Organic farming [1=yes; 0=no]	0.21	0.25	-0.09	0.19	0.17	0.05	0.39	0.00
Specialisation arable farming [1=yes; 0=no][a]	0.37	0.27	0.20	0.36	0.35	0.04	0.39	0.33
Labour intensity [workforce/ha UAA][b]	0.04	0.07	-0.39	0.03	0.03	-0.07	0.11	0.17
Use of extension services [1;5][c]	3.00	2.36	0.52	2.95	2.94	0.01	3.39	1.00
Formal agricultural education [1=yes; 0=no]	0.78	0.66	0.28	0.81	0.82	-0.01	0.57	0.33
Highest educational degree [1;3][d]	2.42	2.02	0.44	2.40	2.47	-0.08	2.57	1.67
Farming experience [years]	26.82	28.00	-0.09	26.78	26.93	-0.01	27.07	25.00
Regional attachment [1;10][e]	8.88	8.68	0.10	9.09	8.99	0.05	7.43	7.33
Environmental awareness [1;10][e]	7.20	6.66	0.20	7.21	7.21	0.00	7.14	4.67
Entrepreneurial attitude [1;10][e]	6.39	4.93	0.70	6.48	5.99	0.23	5.80	3.33
N	221	44		193	193		28	3

[a] According to the self-assessment of the farmer.
[b] Workforce below 1 person is summarized as 1.
[c] 1=never; 2=sometimes; 3=occasionally; 4=often; 5=very often
[d] 1=lower secondary or intermediate education or no degree; 2=high school degree; 3=university degree
[e] Self-assessment questions for which respondents indicated the degree of agreement on a scale from 1=fully disagree to 0=fully agree
Source: Own representation based on farm survey data.

Part II: Robustness check of eco-efficiency results

To check the robustness of the eco-efficiency results, we considered seven scenarios and recalculated the results accordingly:

1. Sampling: exclusion of farms sampled via newsletters of farming associations
2. Spatial heterogeneity: exclusion of farms from Schleswig Holstein and Lower Saxony

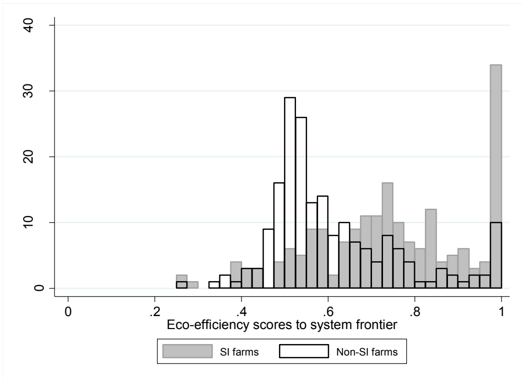
3. Heterogeneity of farm types: exclusion of fully specialised farms, that is those having either only grassland or only arable land
4. SI threshold: Definition of SI adopters if 3 or more SI measures are adopted
5. SI threshold and heterogeneity of farm types: Definition of SI adopters if 4 or more SI measures are adopted AND exclusion of fully specialised farms as they might not be able to adopt the full portfolio of SI measures
6. Weighting of the ecological outcome indicator: 80% on-land diversity and 20% on-farm diversity
7. Weighting of the ecological outcome indicator: 20% on-land diversity and 80% on-farm diversity

The original result refers to all sampled farms, the threshold for SI is set at two or more measures, and the indicator is weighted 50% on-land diversity and 50% on-farm diversity. Refer to sub-section 4.3.1 for more details.

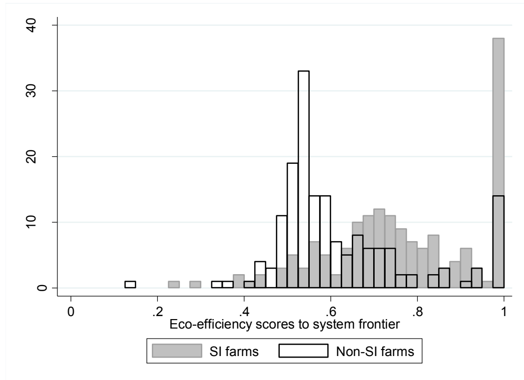
Table E.2 Average eco-efficiency results of the robustness check

Scenarios	N not matched	N matched	Meta technology ratio	Eco-efficiency to system frontier	Eco-efficiency to group frontier
original SI	*221*	*193*	*1.00 (0.00)*	*0.75 (0.18)*	*0.75 (0.18)*
no SI	*44*	*193*	*0.77 (0.13)*	*0.61 (0.15)*	*0.80 (0.14)*
1 SI	198	167	0.99 (0.04)	0.77 (0.17)	0.78 (0.18)
no SI	41	167	0.82 (0.14)	0.62 (0.16)	0.76 (0.14)
2 SI	203	177	0.99 (0.03)	0.77 (0.17)	0.77 (0.18)
no SI	42	177	0.80 (0.13)	0.64 (0.16)	0.80 (0.14)
3 SI	165	143	1.00 (0.02)	0.76 (0.17)	0.77 (0.17)
no SI	21	143	0.72 (0.12)	0.61 (0.11)	0.84 (0.11)
4 SI	157	149	0.99 (0.02)	0.75 (0.17)	0.76 (0.17)
no SI	108	149	0.86 (0.13)	0.63 (0.10)	0.74 (0.15)
5 SI	74	140	1.00 (0.01)	0.84 (0.14)	0.84 (0.14)
no SI	112	140	0.88 (0.06)	0.70 (0.13)	0.79 (0.12)
6 SI	221	193	1.00 (0.00)	0.74 (0.19)	0.74 (0.19)
no SI	44	193	0.80 (0.14)	0.63 (0.15)	0.80 (0.16)
7 SI	221	193	1.00 (0.00)	0.60 (0.25)	0.60 (0.25)
no SI	44	193	0.74 (0.16)	0.49 (0.18)	0.68 (0.22)

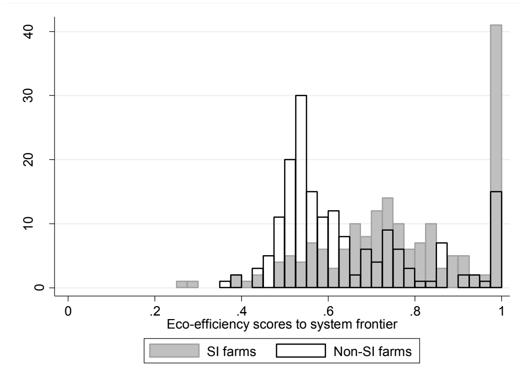
Note: Standard errors in parentheses.
Source: Own representation based on farm survey data.



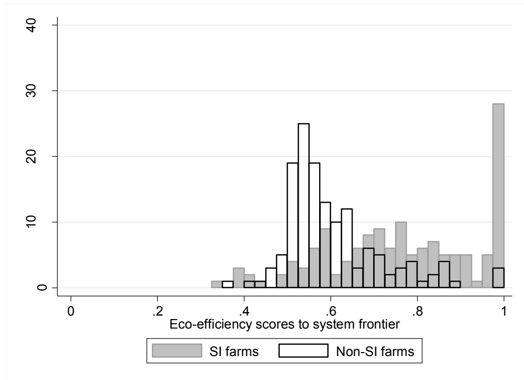
a) Original (N=193 per group)



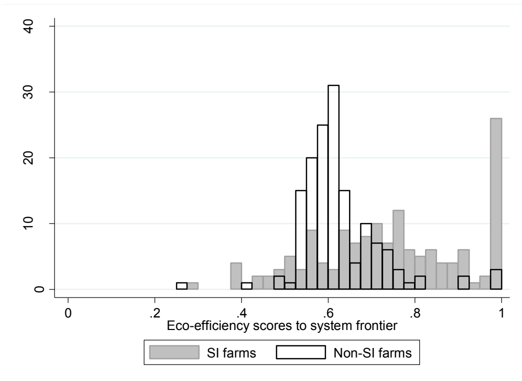
b) Scenario 1: Sampling (N=167 per group)



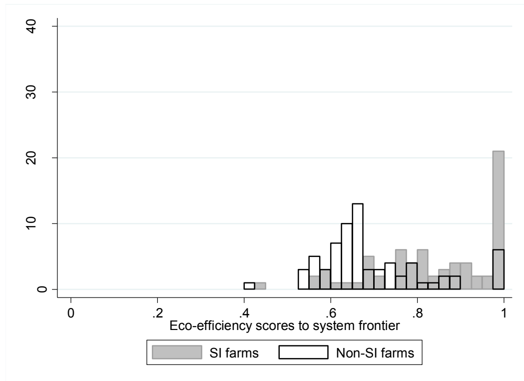
c) Scenario 2: Spatial heterogeneity (N=177 per group)



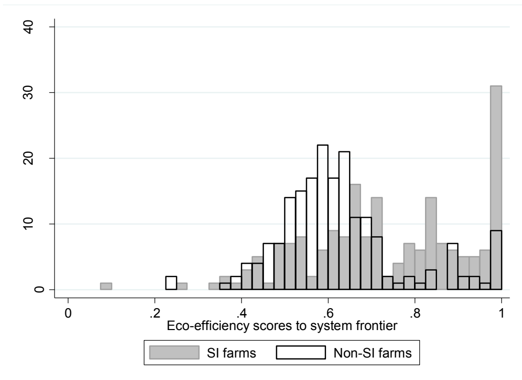
d) Scenario 3: Farm type heterogeneity (N=143 per group)



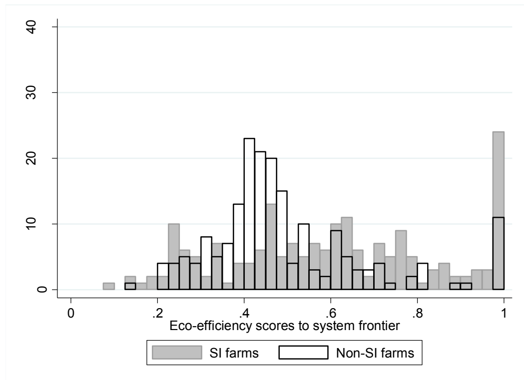
e) Scenario 4: SI threshold (N=193 per group)



f) Scenario 5: SI threshold and farm type heterogeneity (N=140 per group)



g) Scenario 6: Indicator weighting 80:20 (N=193 per group)



h) Scenario 7: Indicator weighting 20:80 (N=193 per group)

Figure E.1 Distribution of eco-efficiency scores to the system frontier for SI and non-SI farms for different scenarios.
Source: Own representation based on farm survey data.

Part III: Eco-efficiency in the direction of the economic output

Table E.3 Eco-efficiency scores in the direction of the economic output for SI adopters and their matched controls

	SI farms		Non-SI farms	
	Mean	Std. dev.	Mean	Std. dev.
Meta-technology ratio	0.98	0.11	0.59	0.17
Eco-efficiency to system frontier/ improvement potential	0.54	0.34	0.39	0.20
Eco-efficiency to group-specific frontier/ within-technology performance	0.56	0.34	0.65	0.24
N	193		193	

Note: Wilcoxon rank-sum test for differences between SI and non-SI farms has a p-value < 0.01 for all three measures.
Source: Own representation based on farm survey data.