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CLIMATE CHANGE AND AGRICULTURAL STRUCTURAL CHANGE: THE RELEVANCE FOR MACHINERY USE AND ACQUISITION IN GERMANY

Dissertation

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Summary

This thesis is a contribution to the research project “Regional Climate Change,” funded by the German Research Foundation (*Deutsche Forschungsgemeinschaft, DFG - Forschergruppe 1695 Regionaler Klimawandel*). The project’s objective was to learn about the vulnerability and sensitivity of typical land systems in Southwest Germany and identify suitable strategies for adaptation. The doctoral work contributes with empirical and methodological insights of farmers’ likely management adaptations in light of the farm managerial challenges arising from climate and structural change in Germany.

The agricultural structure in Germany has strongly changed in the last 60 years. Where before numerous small-scale and labor-intensive farms were observed, it is now the place where fewer and highly mechanized farms contribute to agricultural production. The ongoing agricultural structural change in Germany is characterized by a trend in which many farms exit the agricultural sector, and the remaining –growth-oriented– farmers take over the land, reorganize their farm business, and expand their operations. Nevertheless, this trend of farm growth, which is expected to continue in the future, poses significant challenges at the farm management level: Decisions on machinery use and acquisition play a crucial role in shaping the farm cost structure, and represent a critical element for maintaining competitiveness. Particularly for the expansion efforts, farm managers face a highly complex decision-making process to acquire the proper machinery capacities for field operations.

Moreover, an additional factor will need to be considered for adequate decision-making: Climate change developments and the uncertainties associated with this process will likely increase the complexity of the farmers’ decision-making regarding the best re-organizational strategies towards farms expansion. Changes in the natural conditions for crop growth and development will likely result in management adaptations, e.g., changing the timing for fieldwork operations or changing land-use patterns.

An analysis of the complex interactions and interdependencies between the environment and the farm system, on the one hand, and the resources and production possibilities available to the farm manager in the course of farm expansion on the other hand, require adequate tools of analysis. This work analyzes three dimensions of farm machinery management in the context of climate change and agricultural structural change. The first element of analysis corresponds to an examination of the sensibility of land-use and machinery investment decisions to climate change scenarios with the agent-based MPMAS model constructed for Central Swabian Jura in Southwest Germany. The Central Swabian Jura MPMAS model is a constitutive part of the bioeconomic modeling system MPMAS_XN. The MPMAS_XN system integrates the agricultural economic agent-based software MPMAS and the plant-soil modeling software Expert-N (XN) into a fully coupled system. The assessment of the sensibility and responsiveness of the MP-

MAS component revealed complex adaptation responses of land-use and machinery investment decisions as a result of shifted timing in fieldwork operations (e.g., harvesting or fertilization tasks).

The second element of analysis corresponds to an examination of economies of size arising from farm machinery use and acquisition decisions in arable farms that follow a typical crop rotation practiced in Germany. For the analysis, a whole-farm multiperiod mathematical program implemented in the agent-based software MPMAS was employed. Optimizations were run and evaluated at a broad range of farm sizes and two distinctive distributions of availability of fieldwork days estimated for Southwest Germany. The results allowed observing patterns of optimal farm machinery demand and cost curves for several evaluated farm sizes and distributions of available fieldwork days distributions.

The third main element of this work corresponds to a methodological contribution to the MPMAS_XN model system. Within this element, the implementation, functioning, and potential of an external theory-based MPMAS module are presented. The external module represents dynamics for joint machinery investments among simulated farm agents and serves as an enhancing methodological contribution for analyzing and representing farm machinery management in the agent-based software MPMAS.

Zusammenfassung

Diese Arbeit ist ein Beitrag zum von der Deutschen Forschungsgemeinschaft geförderten Projekt „Regionaler Klimawandel“, dessen Ziel es war die Verwundbarkeit und Sensitivität typischer Landsysteme in Südwestdeutschland zu untersuchen und geeignete Anpassungsstrategien zu identifizieren. Diese Doktorarbeit liefert empirische und methodische Erkenntnisse über die wahrscheinlichen Managementanpassungen der Landwirte und Landwirtinnen angesichts der Herausforderungen der Betriebsführung, die sich aus dem Klima- und Strukturwandel in Deutschland ergeben.

Die Agrarstruktur in Deutschland hat sich in den letzten 60 Jahren stark verändert. Wo früher zahlreiche kleine und arbeitsintensive Betriebe beobachtet wurden, tragen heute weniger, dafür aber hochmechanisierte Betriebe zur landwirtschaftlichen Produktion bei. Dieser anhaltende landwirtschaftliche Strukturwandel in Deutschland kennzeichnet sich dadurch, dass viele Betriebe den Agrarsektor verlassen und die verbleibenden, wachstumsorientierten Landwirte und Landwirtinnen die Produktion übernehmen, ihre Betriebe neu organisieren und ihre Tätigkeiten ausweiten. Dieser Wachstumstrend, der sich voraussichtlich in Zukunft fortsetzen wird,hat erhebliche Herausforderungen auf der Ebene des Betriebsmanagements zur Folge: Entscheidungen über den Einsatz und die Anschaffung von Maschinen spielen eine entscheidende Rolle bei der Gestaltung der Betriebskostenstruktur und sind daher ein zentrales Element für die Aufrechterhaltung der Wettbewerbsfähigkeit. Insbesondere bei den Expansionsbemühungen stehen die BetriebsleiterInnen vor einem hochkomplexen Entscheidungsprozess, um die passenden Maschinenkapazitäten für den Feldeinsatz zu erwerben.

Neben dem Erwerb und der optimalen Nutzung von Maschinen muss ein zusätzlicher Faktor für eine angemessene Entscheidungsfindung berücksichtigt werden: Die Entwicklung des Klimawandels und die mit diesem Prozess einhergehenden Unsicherheiten werden die Komplexität der Entscheidungsfindung hinsichtlich der besten Umstrukturierungsstrategien für die Expansion der landwirtschaftlichen Betriebe vermutlich weiter erhöhen. Dadurch entstehenden Änderungen der natürlichen Bedingungen für Pflanzenwachstum und -entwicklung wird wahrscheinlich mit Anpassungen des Managements begegnet, z.B. durch Verschiebung derFeldarbeitszeitpunkte oder durch Veränderung der Landnutzungsmuster.

Eine Analyse der geschilderten komplexen Wechselwirkungen und Abhängigkeiten, einerseits zwischen Umwelt und landwirtschaftlichen Systemen, andererseits zwischen Ressourcen und Produktionsmöglichkeiten, die den Verantwortlichen zur Betriebserweiterung zur Verfügung stehen, erfordert geeignete Analysewerkzeuge. Diese Arbeit analysiert drei Dimensionen des Landmaschinenmanagements im Kontext des Klimawandels und des landwirtschaftlichen Strukturwandels. Im ersten Analyseelement wird die Sensibilität von Landnutzungs- und Maschineninvestitionsentscheidungen in Bezug auf verschiedene

Klimawandelszenarien untersucht. Diese Analyse wird mit dem agentenbasierten MPMAS Modell durchgeführt, das für die mittlere Schwäbischen Alb in Südwestdeutschland erstellt wurde. Das MPMAS- Modell ist ein wesentlicher Bestandteil des bioökonomischen Modellierungssystems MPMAS_XN. Das MPMAS_XN Modellierungssystem integriert die agrarökonomische, agentenbasierte MPMAS Software und die Pflanzen-Boden-Modellierungssoftware Expert-N (XN) in ein vollständig gekoppeltes System. Die Bewertung der Sensibilität und Reaktionsfähigkeit der MPMAS-Komponente zeigt komplexe Anpassungsreaktionen von Landnutzungs- und Maschineninvestitionsentscheidungen als Ergebnis eines verschobenen Zeitplans bei Feldarbeiten (z. B. Ernte- oder Düngungsaufgaben).

Im zweiten Schritt befasst sich die vorliegende Arbeit mit einer Untersuchung der Skaleneffekte, die sich aus den Kaufentscheidungen und dem Einsatz von Landmaschinen in Ackerbetrieben ergeben, in denen eine für Deutschland übliche Fruchtfolge angebaut wird. Für die Analyse wird ein in der agentenbasierten Software MPMAS implementiertes mathematisches Mehrperiodenprogramm für den gesamten landwirtschaftlichen Betrieb verwendet. Optimierungen werden in einem breiten Spektrum von Betriebsgrößen und zwei unterschiedlichen Verteilungen der Verfügbarkeit von Feldarbeitstagen, die für Südwestdeutschland geschätzt werden, durchgeführt und bewertet. Die Ergebnisse ermöglichen die Beobachtung von Mustern der optimalen Nachfrage nach landwirtschaftlichen Maschinen sowie der Kostenkurven für die betrachteten Betriebsgrößen und Verteilungen der verfügbaren Feldarbeitstage.

Der dritte Hauptteil dieser Arbeit stellt einen methodischen Beitrag zum MPMAS_XN Modellsystem dar. In diesem Element werden die Implementierung, Funktionsweise und das Potenzial eines externen und theoretisch aufgebauten MPMAS-Moduls vorgestellt. Dieses externe Modul repräsentiert die Dynamik, die sich aus gemeinsamen Maschineninvestitionen zwischen simulierten Computer-Agenten ergibt und dient als verbesserter methodischer Beitrag zur Analyse und Darstellung des Landmaschinenmanagements in der Agentenbasierte Software MPMAS.

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This work is dedicated to my parents, María Suyapa Tijerino Verdugo and Francisco Antonio Mendoza Velásquez, and siblings, Daniela and Alejandro Mendoza Tijerino; thank you for your unconditional love and support.

Francisco Antonio Mendoza Tijerino,
Stuttgart-Hohenheim, September 2020

"*Dijo Julio Antonio Mella: «Si me pongo retrechero, no perdone, camarada, ni el más leve parpadeo; si ves que avanzo, seguime, si me detengo, empujame, y si acaso retrocedo, ahí mismo liquidame».*"

No se me raje mi compa,
Carlos Mejía Godoy

Climate Change and Agricultural Structural Change: The Relevance for Machinery Use and Acquisition in Germany

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Contents

1.1 Background information

This doctoral thesis is a contribution to the research project "Regional Climate Change," and particularly to the sub-project "Integrated Land System Modeling (P8)" funded by the German Research Foundation (*Deutsche Forschungsgemeinschaft, DFG - Forschergruppe 1695 Regionaler Klimawandel*). The project was conceived in order to address the effects of climate change on typical agricultural land systems in Southwest Germany, and it emphasizes the need to improve the understanding regarding the effects of climate change and variability on a regional scale. Moreover, the project aimed to learn about the vulnerability and sensitivity of these typical land systems with a focus on learning about suitable strategies for adaptation.

The sub-project "Integrated Land System Modeling (P8)" was under the leadership of the Chair of Land-Use Economics (Josef G. Knoll Professorship). The aim under sub-project P8 was to combine different model components from the various other projects of the research group into an integrated model system and to use computer simulations to investigate and learn about the interactions and feedback of biophysical and socio-economic processes.

1.2 Problem statement and motivation

This Ph.D. thesis is motivated by two developments of the framework conditions in which farmers in Germany are currently involved. These two developments are climate change and agricultural structural change. From the perspective of climate change, the work focuses on the implications of two manifestations that have the potential to trigger significant farm-reorganization strategies; these manifestations are: i) The change in the phenological development of crops and the associated trend of shifts in the ideal timing for fieldwork operations, and ii) the changes in the availability of fieldwork days for weather-sensitive field operations.

Regarding the change in the phenological development of crops and the associated shifts in the ideal fieldwork timing, the interest rests in investigating their relationship to the adaptation of land-use and farm machinery acquisition. Farm machinery selection has been acknowledged as one of the most challenging farm management problems due to the significant implications it has in shaping farms' competitiveness (Kay et al., 2004). Modified crop-growing periods resulting from climate change developments will likely affect the timing for performing fieldwork operations in agriculture and have the potential to drive revisions in the optimal machinery portfolios and investments of farmers. For example, longer growing seasons can result in crop damage due to the associated higher temperatures and longer plant exposure to sun, which in turn may require farm management revisions in sowing and harvesting scheduling and operations (Mueller et al., 2015).

Likewise, the warmer temperatures manifesting as results of climate change are expected to affect the general phenological development of crops. The changes in the vegetation days of crops can modify, for example, the ideal timing of sowing, harvesting and fertilization operations, and can drive to situations where there is an accumulation of fieldwork tasks that need to be completed in a specific time window and that compete for limited resources (e.g., equipment capacities). Plant phenological changes can also redefine the currently established crop rotations. For instance, in Southwest Germany, a longer growing season could trigger two appropriate fieldwork responses depending if the crop is a winter or a spring crop. For spring crops (e.g., spring barley, silage maize), it is expected that the elongation of the crop growing season and the phenological crop changes resulting from warmer conditions result in earlier sowing and earlier harvesting operations (Troost et al., 2020). In the case of winter crops (e.g., winter wheat, winter barley or winter rapeseed), the longer growing seasons will likely shift the buffer of days in which it is adequate to sow towards the end of the year, meaning that later sowing fieldwork operations should be expected. For instance, farmers in Southwest Germany may be able to engage in the production of winter rapeseed after wheat if warmer conditions would allow it; a crop rotation that is currently difficult to achive in regions like the Central Swabian Jura. Under current climatic conditions, the harvesting dates of winter wheat and the sowing dates of winter rapeseed collide or do not allow for a proper time frame for stubble tillage operations, however, small shifts in the harvesting days of winter wheat could permit the timely sowing of rapeseed. Changes in the crop rotations could potentially affect farm machinery use and acquisition, and therefore significantly impact the cost structure of the farms, hence, limiting the scope for further adaptation to climate change.

The acknowledged expectation for future climatic conditions can be summarized in two trends – in particular for the northern hemisphere of the planet: i) A more volatile climate (expected more variability in climatic conditions) and, within this volatility, ii) warmer average conditions. These warmer conditions, in turn, will likely induce longer growing seasons for crops and important changes in crop phenological development.

Moreover, climate change may not only affect the timing of fieldwork due to shifts in the growing season and phenological plant development. Climate change will also have implications in the number of days with suitable weather that farmers will have in order to perform fieldwork operations. The analysis of the changes in the availability of fieldwork days and their impact on farm machinery use and acquisition is the second aspect of climate change that is dealt with in this work. As Troost and Berger (2015) showed, considering non-yield effects of climate change such as changes in the availability of fieldwork days is essential to understand the adaptation decisions in farm management. Farmers may adapt their crop management strategies to cope with tighter or exploit more extensive time windows for fieldwork operations, and, as a consequence, they may require adjustments in their optimal machinery portfolio to either increase fieldwork capacity or save resources using smaller equipment.

In addition to the expected future climate change developments and their potential impacts on the farm machinery management, the ongoing agricultural structural change in Germany reveals a context in which farm managers face complex decisions regarding their continuity in the farming business. Farm businesses that experience financial pressure and go bankrupt, farm managers that lack a successor or farm businesses that have high opportunity cost due to occupations outside agriculture typically exit farming, while the remaining, growth-oriented, farms take up the idle land, reorganize their businesses and expand their agricultural operations. In 1980 there were approximately 836,500 farm holdings in Germany managing an average farm size of 14.6 hectares, in 2016 there were 275,000 farm holdings that managed, on average a 60.5 hectares (BMEL, 2019). This observed trend of farm growth over the last decades in Germany suggests that economies of size are eventually achieved, and, hence, the segment of farms that acquire these economies of size experience decreasing long-run average costs as they decide to expand. Yet, the extent to which economies of size can be attained and exploited by growth-oriented farm managers depends significantly on their capacity to make full use of their resources – and justify their use–, especially the use of farm machinery and specialized equipment given their nature of non-divisible factors of production.

Considering these developments, it can be stated that farmers in Germany currently face complex adaptation challenges triggered by climate change developments in the context of agricultural structural change. These two processes shape the conditions in which farming is practiced. The conceptual framework presented in Figure 1.1 organizes the relevant elements and the relationships that guide, give meaning, and highlight the rationale of this doctoral work. As a starting point, it is considered that climate change is a process that will potentially alter achievable yields, temperature levels, length of the growing season, and the intensity of precipitation levels. The expected changes in the biophysical elements of the farm system have the potential to modify the existing socio-economic dimension of the system. New yields, different trends in precipitation intensities, or a shifts of the plant growing stages and season may result in modifications of the –economically– adequate land-use patterns. Also, biophysical changes have the potential to affect the relative profitability of farm enterprises (crops, livestock, bioenergy). These potential effects imply reorganizational efforts for the farm managers and trigger managerial challenges at all levels (e.g., tactical and strategic decision making, acquisition of resources for farm management, human resource management, machinery management, land control and use).

Farm survival and economic prosperity require sound and adequate management in a changing climatic context; failing to do so can place the farm business in a competitive disadvantage, which may lead to financial difficulties (Kay et al., 2004). Søgaard and Sørensen (2004) recognize farm machinery management as one particular complex managerial process within the overall challenges of farm management. Decisions on the adequate acquisition of farm capacity typically involve strategic investment decisions that have a significant effect on the cost structure of the farms and fix resources for an extended period while affecting the future capacity to adapt to environmental changes and the efficiency of on-farm resource use. Therefore, efficient farm machinery management can have far-reaching implications in the capacity of the farm to generate an adequate income level, define its competitiveness and ultimately shape the decisions of the farm manager to either continue or exit agriculture, hence generating feedback effects on the course of agricultural structural change.

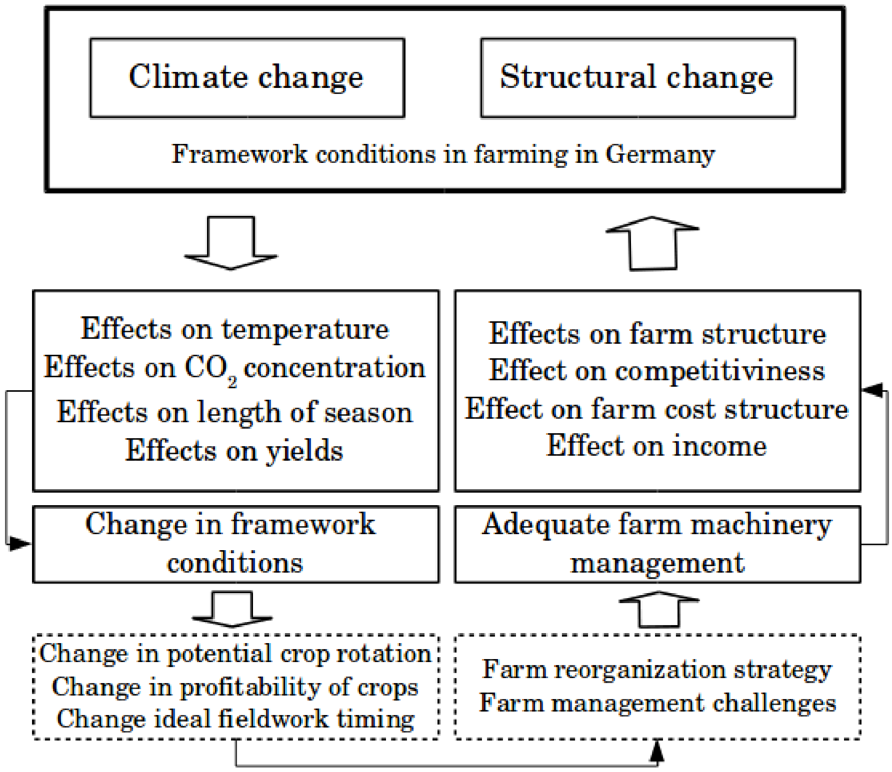

Figure 1.1: *Conceptual framework for a framing of the relationship between climate change and agricultural structural change in this doctoral work.*

1.3 Research questions and objectives of this doctoral thesis

This Ph.D. thesis contributes on two fronts of the challenges that arise in the examination of the effects of climate change adaptation in the context of agricultural structural change in Germany. While the work is empirically driven and motivated (Section 1.2), the doctoral thesis exhibits one empirical component (defined by research objectives one and two) and one methodological component (defined by the research objective number three).

1.3.1 Rationale for the formulation of the research objectives

The rationale behind the formulation of the first objective was based on the need to explore and examine the potential effects that shifted dates of ideal timing for fieldwork operations can have on the land-use and machinery acquisition decisions of a simulated farmer in the Central Swabian Jura region in Southwest Germany. The analysis is performed by examining the responsiveness of land-use and machinery acquisition patterns employing simulation analysis with the agent-based modeling software Mathematical Programming-based Multi-Agent Systems (MPMAS). Once insights are gained for this climate change dimension, the second objective was conceived to improve understanding on another dimension of analysis; namely, the examination of the trends of farm machinery and equipment investment decisions resulting across various farm sizes (i.e., across the path of growth of a farm business). Furthermore, in the context of the second objective, it is intended to derive insights on the interplay between machinery acquisition and the shaping of economies of size derived from farm mechanization in the context of distinctive trends of climatic variability for Southwest Germany. The analysis performed is based on optimization runs employing the agent decision module of the MPMAS software.

Objective number three was established to further enhance the modeling framework of MPMAS and presents a methodological approach for the analysis of farm machinery management in Southwest Germany. The need to represent farmer-to-farmer interaction in machinery sharing dynamics is the driving force for the establishment of the third objective in this work.

Research question 1 and specific objective:

How do simulated land-use patterns and farm machinery investment decisions respond to various climate change scenarios implemented in the MPMAS model component of the bioeconomic modeling system, "MPMAS_XN"?: Due to changes in the plant growing season resulting from warmer conditions, the phenological development of many crops might accelerate and require adaptation of timing of fieldwork operations. In the context of this research question, the objective is to perform a detailed and extensive examination of the sensibility of the MPMAS model component of the MPMAS_XN model system. This is performed by examining the relevant responses of land-use and machinery investment outcomes derived from implementing and using the dynamic fieldwork operations feature of the model MPMAS model constructed for the Central Swabian Jura in Southwest Germany. This research objective aims to address the methodological need to perform sensitivity analysis for the purposes of the model integration between the MPMAS and Expert-N (XN) software.

Research question 2 and specific objective:

How do farm machinery investment decisions and economies of size derived from farm mechanization are shaped across a wide range of farm sizes in the context of distinctive time windows affecting the performance of weather-dependent fieldwork operations?: Economies of size in farming can result from various reasons; for this research question, the objective is to analyze economies of size arising from the decisions of farm machinery use and acquisition in arable farms that follow a typical crop rotation practiced in Germany. The effect that modified time windows for weather-dependent field operations may have on the investment decisions in farm machinery and economies of size is further analyzed regarding two typical distributions of available working days for Southwest Germany.

Research question 3 and specific objective:

How can farm machinery associations be modeled in the MPMAS modeling framework in the context of scarce data availability?: Farm machinery associations are an essential approach to cooperative arrangements that farmers perform in order to deal with the capacity control of lumpy technologies (e.g., tractors, combine harvesters, seeding equipment). Detailed data on the functioning, drivers, and economic impact of these types of arrangements are typically not available, yet, such associations are common and represent a relevant approach to farm machinery management. The objective within this research question is to present the implementation, functioning, and potential of an external theory-based MPMAS module implemented in the *Mpmasql*4 tool for the representation of joint machinery investments among simulated farm agents.

1.4 Structure of this Ph.D. thesis

This thesis is divided into five core chapters and an additional section for supporting information. The first and current chapter, "Introduction," presented the framing conditions that gave rationale and motivation to the research work. The first chapter also presented the research questions and objectives. The second chapter, "Climate and Structural Change", discusses three topics: i) Climate change, ii) agricultural structural change, and iii) the relationship between farm machinery management and climate change. The first two topics of chapter two serve to contextualize and review the literature discussing the ongoing trends in which farming occurs, with a special focus on Germany and other countries that manifest trends of agricultural structural change and have achieved successful farm mechanization states. The third topic combines insights gained from the first and second topics into a presentation of the theoretical pathways in which farm management and, especially, machinery management, can react to climate change in the course of agricultural structural change.

Chapter three, "Simulation and optimization analysis," presents the examination of two constitutive elements of farm machinery use and acquisition in the context of climate change and agricultural structural change: The first section of chapter three analyses the sensitivity of the constructed recursive-dynamic agent-based MPMAS model for the Central Swabian region in Southwest Germany to distinctive trends of shifts in fieldwork operation times on machinery investments and land-use patterns. The second section of chapter three provides an analysis of economies of sizes in farm mechanization in Germany in accordance to the research question and objective number two.

Chapter four presents the arguments for the representation of farmer-to-farmer cooperation for farm machinery sharing in simulation analysis dealing with climate change and structural change. The fourth chapter introduces the implementation and functioning of an external module for agent-to-agent interaction for the MPMAS software designed to represent joint investments in assets for the formation of machinery sharing groups among simulated farmers. Chapter five provides a discussion of findings and the contributions of this doctoral thesis, as well as conclusions and further research perspectives. In chapter six, the documentation, annexes, and additional necessary support information are provided.

Chapter 2

Climate and structural change

Contents

2.1 Climate change and agriculture

2.1.1 The climatic framework conditions for the farm system

In the contribution "Farm Systems and Poverty: Improving Farmer's Livelihoods in a Changing World," Dixon et al. (2001) recognize the farm system as a complex organization constituted by three main elements: A decision-making unit (typically the household, or farm manager), its available resources, and all the interactions among these resources. Under this perspective, all the biophysical, socioeconomic, and human factors available to the farm are parts of the system's resources, which manifest multiple interdependencies in the form of competition or complementarities in the process of sustaining a –relatively– controlled agroecosystem.

From the agroecological perspective, sustaining an ecosystem that serves the production of crops depends on a diversity of factors. Biotic (e.g., accompanying plants, phytophages, pathogens) and abiotic (e.g., light, water, temperature, nutrients, soil) factors are fundamental for plant growth and development, yet, their availability and use-intensity for the plants are only partially controlled by farmers' managerial capacity: The climatic conditions are a central determinant of the success or failure of the agroecosystems since they define the availability of the majority of the natural resources and agroecological processes that are essential for plant growth and development (Martin and Sauerborn, 2006).

The current agroecosystems that define today's land cover and land use patterns are adapted to the prevailing climate trends of variability within particular temperature levels and rainfall intensities, yet, the ongoing anthropogenic-induced climate change will likely result in warmer climatic conditions, higher CO_2 concentration in the atmosphere, higher weather varibility, and will potentially affect agricultural production at various, sometimes difficult to predict, levels (Martin and Sauerborn, 2006; IPCC, 2001; Kurukulasuriya and Rosenthal, 2013).

2.1.2 Anthropogenic-induced climate change

Trends of global climate

The global temperature change between 1850 and 2018 with respect to the average temperature between 1961-1990 has been increasing since the first half of the 20th century and it recorded in 2018 an average difference of 0.8 degrees Celcius in relation to the benchmark period of 1961-1990 (Hadley Center, 2020). Observable effects of the warmer conditions are, among others, the increase of the average sea level between 10 and 20 cm, warmer conditions and the extension of the vegetation period in the Northern Hemisphere in about 1-4 days per decade in the last 40 years (Martin and Sauerborn, 2006).

Based on multiple modeling results comprising distinct plausible scenarios of CO_2 emissions, the institutional body of assessment of climate change, the Intergovernmental Panel on Climate Change IPCC (IPCC, 2014), projects that the average global mean surface temperature change by the end of the 21st century (2081–2100) relative to the 1986-2005 period will range between 0.3 and 4.8 degrees Celcius, depending on the scenario evaluated. Furthermore, longer lasting and more recurrent heatwaves are likely to derive from the increase in the global temperature and extrem precipitation events are expected to be more frequent in many regions of the planet.

Trends of regional climate change for Germany

The "Regional Climate Projections Ensemble for Germany" (ReKliEs-De) – *"Regionale Klimaprojektionen Ensemble für Deutschland"* (Hübener et al., 2017) was an effort to assess the climate change signals for the end of the 21st century (2071–2100), and it examined relevant indicators of climate change in comparison to the reference period 1971–2000 for the ReKliEs-De area (Germany and the river catchment areas draining into Germany). The EURO-CORDEX - ReKliEs-De Ensemble represents, due to its size, its high spatial resolution, and the combination of statistical and dynamic regionalization processes, a globally unique database for research into climate change (Hübener et al., 2017).

Two global scenarios were communicated in their final report. A *"Continue as before"* scenario and a *"Climate protection"* scenario show two differentiated trends for comparison. In terms of temperature, the *"Continue as before"* scenario predicts an increase in the annual mean temperature at almost 4 degrees Celsius, whereas the scenario *"Climate protection"* predicts a warming increase of 1 degree. In general, the results from the models suggest that heat periods will increase, and cold periods will decrease or disappear (Hübener et al., 2017). Regarding the expected precipitation, most of the model simulations suggest a reduction in precipitation levels in Summer and an increase in Winter. Moreover, the amount of precipitation during heavy rain phases is expected to increase more strongly than the average amount of precipitation (Hübener et al., 2017).

2.1.3 Potential climate change effects on agriculture and farm management

Climate change can impact agriculture in a variety of ways. Moreover, these potential effects have been widely investigated and documented among scientific circles dealing with agriculture and agricultural economics. Climate change is responsible for affecting terrestrial (agro) ecosystems, and it comprises increased frequency and intensity of extreme weather conditions that create additional stress on agricultural production and call for adaptive mechanisms to cope with higher weather variability (IPCC, 2019). The effects of climate change on agriculture can be classified into three main categories: i) Effects at the crop level, ii) effects at the agroecosystem level, and iii) effects at the management, production conditions, and yield level (Martin and Sauerborn, 2006).

Climate change effects at the crop level

At the crop level, plants can be further classified into two main categories depending on their biochemical energy dynamics: C3 and C4. C4 plants are more efficient than C3 plants in capturing CO_2 from the air; however, C4 plants are less efficient than

C3 plants in converting light into energy (Institute for Crop Production and Grassland Research, University of Hohenheim, 2006). In several regions located at low latitudes, there is evidence that reveals that the changes in weather conditions induced by past manifestations of climate change have resulted in reduced crop yields (e.g., for wheat or maize), whereas in some regions located at higher latitudes, there are cases where crop yields have actually increased (e.g., for sugar beets, maize, wheat) or are expected to increase as result of CO_2 effects (IPCC, 2019; Harrison and Butterfield, 2000). Moreover, alone the doubling in the concentration of CO_2 in the atmosphere can potentially increase the achievable yield of C3 plants (e.g., wheat) (Downing et al., 2000) if other climate change-dependent factors (e.g., water supply, temperature) are constant, yet, further increases in the CO_2 levels above the optimal temperature for CO_2 fixation for these plants can result in the yield potential reductions.

For C4 plants is the increase of CO_2 concentrations in the atmosphere of marginal importance if one only considers the CO_2 effect of climate change (Martin and Sauerborn; 2006), yet, it can not be ruled out that other factors like changed rainy patterns or effects on soil erosion will also have significant effects on yields.

From a critical perspective, Zebisch et al. (2005) report that studies addressing the impact of climate change on agriculture in the specific case of Central Europe predict an increase on the yield of wheat on about one and three tones per hectare. However, these authors argue that important variables like water stress and the risk of yield losses have not been adequately considered in most of the assessments of the effects of climate change on agriculture for Central Europe. For the specific region of Baden Wuerttemberg in Southwest Germany, Zebisch et al. (2005) further report that by considering the effect of water stress in Summer, estimations from the KLARA project from the Potsdam Institute for Climate Impact Research indicated that the yield of wheat can potentially decrease by 14 percent by the year 2055. This decrease is the result of water stress in a combination of the negative impacts associated with increased temperatures (due to early grain maturity and earlier harvesting).

Climate change effects at the agroecosystem level

The increases in the concentration of CO_2 levels will additionally affect numerous processes taking place at the level of the agroecosystem. For example, the organic carbon stocks stored in the soil will react in different ways to higher CO_2 levels; a likely effect of higher carbon dioxide concentrations is the increased decomposition of organic matter and the reduction of the soil's carbon stock (Olesen and Bindi, 2002). Moreover, higher CO_2 levels have the potential to affect the relationship between weeds and crops. The competition between C3 crops and C4 weeds can be affected by CO_2 variations; an increased supply of carbon dioxide can be translated in lower competition-related yield losses, for the case of C4 crops (e.g., maize, sorghum, or sugar beet) and C3 weeds, the increase in the CO_2 level can translate into a reinforced fertilization effect of the weeds and directly have a negative impact on the yields of crops (Ziska, 2000).

Climate change effects at the management, production conditions, and yield level

At the level of crop management, production conditions, and yields, climate change can affect agriculture by triggering changes across several factors, namely changes in temperature, soil conditions, CO_2, and plant diseases. A temperature-related shift of the climatic zones in Europe will most likely enable an extension of the cultivation areas northwards, beyond today's climatic limits (Maracchi et al., 2005). For instance, Menzel and Fabian (1999) estimate that the average annual growing season has lengthened by 10.8 days since the early 1960s and that these shifts can be attributed to changes in air temperature. It is important to notice that this estimation does not consider the increases in the carbon dioxide concentrations of the last 20 years, and it is expected that this value might be underestimated in today's state of the climate.

Similar observations have been made by Kukal and Irmak (2018). Based in their review, the authors report a consistent lengthening of the plant growing season of an average of two weeks during the 20th century in the continental United States of America. Likewise, and for Europe's case, the European Environmental Agency (2012) indicates that the growing season of several crops has increased on average by 11.4 days from 1992 to 2008 and it is expected that the growing season will continue to enlarge in most of Europe.

Modified growing periods resulting from climate variability and climate change will affect farm management in various ways. Olesen et al., (2012), for instance, investigate the potential changes in time of sowing, flowering, and maturity of selected crops in Europe under climate change; the authors employ climate model projections to assess changes in the timing of crops phenology to 2040, and their results showed advancements of sowing date of spring cereals as well as advances of the timing of flowering and maturity of maize, oats, winter wheat and spring wheat on the interval of 1–3 weeks as a result of warmer climatic conditions. On the other hand, climate change can trigger alternative crop rotations; for example, longer growing seasons resulting from warmer conditions may result in the possibility of double-cropping systems, i.e., having multiple harvests from the same field each year. Moreover, a longer growing season for crops like maize or wheat might allow and require adaptation of sowing operations and earlier harvesting in the year in order to avoid extremely high temperatures (Mueller et al., 2015).

For Southwest Germany, Troost (2014) and Troost and Berger (2014) report, based on expert opinions and farmers' interviews, the possibility of growing rapeseed after winter wheat due to earlier wheat harvest as a result of climate change. Alternatively, a warmer average climate is also likely to impact the growing seasons for specific crops belonging to the roots or tubers families by reducing the time windows in which fieldwork can be achieved for these crop enterprises (Olesen and Bindi, 2002). In Southwest Germany, the state of a longer growing season can suggest two differentiated appropriate fieldwork responses depending on if the crop in question is winter or a spring crop. It is expected that the elongation of the growing seasons results in earlier sowing and earlier harvesting for spring crops. For winter crops, the longer growing seasons due to hotter temperatures will likely shift the buffer of days in which it is adequate to sow forward in the year, meaning that later sowing fieldwork activities will be expected. Harvesting of winter crops is expected to be performed earlier in the year due to the acceleration of the phenological development resulting from higher temperatures (Webber et al., 2018).

Climate change also holds the potential to affect the trend of the variability of suitable weather conditions that farmers will have to perform fieldwork operations. Olesen et al. (2011) acknowledge that climate change will be characterized by increased climate variability and more extreme weather conditions. The impact of tighter time windows for field operations in the U.S Midwest as a result of climate change has meant adaptation of farm machinery management through the investment in larger machinery and equipment for the performance of quicker fieldwork operations (Doll et al., 2017). Moreover, climate change will likely induce other types of investments; Lehmann et al. (2013) argue that decreases in water availability due to decreased precipitation resulting from climate change will likely promote the use of irrigation, in particular for grain maize production. Furthermore, the authors assert that climate change also has the potential to impact fertilization fieldwork operations; maize and winter wheat might require less nitrogen fertilization amounts and a reduced number of applications per year.

The interrelationship between the environmental conditions – that frame the availability of the farm system's natural resources – and the farm management decisions do not only flow in one direction (from the environment to farm); farm management decisions can also influence the environment. Land management decisions can affect the environment in the medium and long term, for example, by creating or avoiding soil erosion (through the choice of specific crop rotations or monocropping), humus decomposition, or nutrient loss (Ingwersen et al. 2011; Foley et al. 2005). Land management practices that allow growing green manure crops and cover crops, or tillage practices that allow crop residue retention such as reduced/zero tillage, play an essential role in the farm's feedback effect towards the environment (IPCC, 2019).

2.2 Agricultural structural change

The previous subsection looked into the natural framing conditions in which farming takes place; these conditions are expected to evolve in complex ways due to climate change while calling for appropriate adaptation pathways on the farmers' side. In this subsection, the focus is placed on the other context in which farming occurs: Agricultural structural change.

2.2.1 Structural change in agriculture: Meaning and relevance

Structural change is the process that characterizes the development of farming in the last decades in Germany. Typically, one can understand this process as one where there is an ongoing trend of decrease in the number of farms in a region or a country, and the size of the remaining growth-oriented farms (usually in respect to the agriculturally used area) increases. In 1980, for example, there were approximately 836,500 farm holdings in West Germany managing an average farm size of approx. 14.6 hectares; in 2016, there were 275,000 farm holdings that managed, on average, 60.5 hectares (BMEL, 2019). Agricultural structural change also relates to reductions in the number of agricultural workers and the contribution of agriculture to the overall economy (Henrichsmeyer and Witzke, 1991; Doluschitz et al., 2011). Often, agricultural structural change additionally manifests in specialization trends of the farms remaining active in the sector.

Based on official statistics from the German Ministry of Nutrition and Agriculture (BMEL, 2017), the reduction in the number of farms in Germany varies along different farm size categories (e.g., 10-20, 20-50, 50-100 hectares). Below 100 hectares, there is a decrease in the overall number of farms businesses between 2013-2010 and 2016-2013 in Germany. The category of farms managing between 20 and 50 hectares is the size category that shows the most substantial decrease in the farm number between 2016-2013 with a -2.3 percent. The number of farms that manage more than 100 hectares is, on the contrary, increasing. For example, the number of farms in the size category of 200-500 hectares showed the strongest increase, 2.9 percent between 2016-2013, among all the increasing farm size categories. Moreover, in the case of agricultural labor, in 2016 there were 940,100 workers occupied in farming in Germany; this corresponds to a 2.7 percent decrease in comparison to 2013.

Understanding the farms' strategic medium and long-term investment decisions is highly relevant if policymakers want to address farm policies' impact in the context of agricultural structural change. Espinosa et al. (2016) argue that the overall impact of agricultural and environmental policies strongly depends on characteristics such as farm size and farm output orientation. Furthermore, the changes in the distribution of the farm structure can also affect regional production levels (e.g., through changes of farm specialization), aggregate employment, tax revenues, or the effect of policy schemas such as type-specific agri-environmental interactions or direct payments (Zimmermann et al., 2009).

Two interrelated elements driving structural change need to be distinguished: On the one hand, the dynamics of entry and exit from the farm sector, and, on the other hand, the expansion or contraction of continuing farms (Weiss, 1999). The next subsection presents a review of the significant theoretical approaches that explain the reasons for farm growth, farm contraction and exit of the farm sector. The theoretical section is later contrasted with the relevant empirical literature addressing agricultural structural change.

2.2.2 Growth and contraction: Why do farmers exit and others grow? Theoretical and conceptual considerations

Pre-considerations

This section provides a look into the relevant theoretical and conceptual approaches that address agricultural structural change. The subchapter's objective is to present the framework conditions in which agricultural structural change takes place and highlight the advantages and difficulties posed by two main approaches (static and dynamic economic approach) used for the understanding of structural change in agriculture.[1]

[1]The concepts "farm structural change", "agricultural structural change" and "changing farm structure" are used interchangeable. Even when each concept has its particular connotations and implications, abtraction is introduced in the aim of an easier reading stream and point to their interchangeable use as long as it is not otherwise explictely indicated.

Drivers and framework conditions

The change in the farming structure can fundamentally be framed and analyzed with respect to the entry and exit of business in the farm sector and the growth dynamics of businesses that remain in farming (Weiss, 1999). These observations place in the foreground the location-dependent nature of farming and underline that a change in the farm structure can only occur as long as an exchange of land takes place – typically through land markets. Through the land exchange, growth-oriented farms take up the land of farms that experience contraction or exit the farming business (Weinschenck, 1989; Huettel et al., 2013; Odening et al., 2015). Under this premise, exploring the nature of farm exit and farm growth incentives is the starting point towards a treatment of the dynamics of agricultural structural change.

It exists extensive literature available on the drivers of structural change in agriculture. Several important factors require attention. For example, technological change and innovation in the form of improved seeds, improved management techniques, or larger and more efficient machinery and equipment enhance efficiency and productivity, and play an important role in reducing the total average cost of production, consequently triggering economies of size conditions that incentivize farms to grow (Zimmermann et al., 2009; Balmann and Valentinov, 2016). Additionally, off-farm employment opportunities or policy interventions and frameworks are often decisive in the definition of the opportunity costs of farming, leading to changed incentives for farms to exit the sector or grow (Appel et al., 2016; Neuenfeldt et al., 2017; Neuenfeldt et al., 2019).

From the farmers' perspective, Kremer-Schillings (2016) attributes the pressure to expand the farm business to the need to secure farmers' economic existence: It is argued that the general cost of inputs required for production has shown continuous increases in the last years in contrast to the barely varying prices for the agricultural output; this development forces farmers to grow and increase their production levels to assure an adequate level of profit.

Cochrane's work (Cochrane, 1958; Cochrane, 1979) has been crucial in explaining agricultural structural change dynamics; his contribution allowed the establishment of important theoretical connections between technology adoption patterns, land market competition, and farms' exit and survival decisions. Under this view, agricultural structural change can be viewed as a situation in which farmers are on a "treadmill." Cochrane argues that, in the aim to improve their incomes, "early adopter" farmers take up new technologies that allow the ripping off of temporal benefits as a result of lower average production costs. However, as more farmers imitate and adopt the technology, product prices decrease (due to an excess of production in the market), and the profits for the average farmer vanish. In this situation, "laggard" farmers that do not get on the "treadmill" and do not adopt new technologies cannot decrease their production costs and are obligated to close operations due to a lack of profitability. In the process of technology adoption, the profits that "early adopter" farmers achieve can drive into efforts towards farm expansion, yet, as more farmers also try to expand, land rents increase and pressure "laggard" farmers to either adopt new technologies, decrease their average production costs, or give up operations (Levins and Cochrane, 1996; Cochrane, 1958). The theory proposed by Cochrane does not, however, consider the degree to which prices of products are sensitive to regional or microregional supply changes, nor adaptation costs or risk are directly considered, yet, it provides a direction to understand the potential dynamics of agricultural structural change.

On a different perspective, Breustedt and Glauben (2007) recognize that structural change can also result from farmers voluntarily leaving farming because of age and health reasons. Moreover, Troost and Berger (2016) underline the relevance of farm succession in the study of structural change in agriculture. Additionally, agricultural policies (e.g., credit programs or income transfers), the managerial capacity, the age structure of a region, the existence of farm successors, the degree of market power of agricultural business, and path dependence have been identified as additional central factors that frame the incentives for farms to either seek growth opportunities or to exit agriculture (Weiss, 1999; Balmann, 1997; Happe et al., 2008; Zimmermann et al., 2009; Troost and Berger, 2016).

Approaches to measuring farm size

The overview presented above on the framing conditions and general structural change drivers place the utilized agricultural area as a central element in the farm size's conceptualization. However, the farm size can have several connotations. For instance, Brandes and Odening (1992) broadly understand the farm size as the totality of the human and material production forces that determine the farms' potential productivity when these are applied to production processes. The concept proposed by these authors suggests that the size of a farm can be measured in many ways. For example, one can use the extent of production factors used in the production process (e.g., value or quantities of labor or capital), the realized output (e.g., quantities of agricultural products or revenue), or traditional economic performance measures (e.g., income, profit).

In Germany, an additional measure that has been established and typically used is the standard farm income (*Standardbetriebseinkommen*). This measure corresponds to the difference between product output (evaluated at standardized costs, prices, and natural yield) and factor use. This measure was introduced in order to overcome the difficulties that arise when measuring farm size with traditional economic measures in phases of volatility (e.g., prices, yields) (Dabbert and Braun, 2012).

Most agricultural economists agree that, in practice, the use of the utilized agricultural area is a measure for farm size that can be appropriately used for comparison purposes as long as farms do not show significant differences in their production orientations. For instance, it would be inadequate in most cases to compare a livestock farmer with a wine farmer on the basis of the land endowment; in Germany, a full-time livestock farmer with 50 hectares belongs to a small segment of farm sizes, whereas a wine farmer with 50 hectares belongs to a segment of big farms (Dabbert and Braun, 2012).

Theoretical approaches to farm growth and contraction

From a theoretical point of view, the traditional neoclassical economic theory offers explanations, not without controversy, of an enterprise's optimal farm size and the incentives to grow or shrink. This theoretical approach has been used to understand and predict farm outcomes (e.g., effects of prices, yields on income, and cost levels) and predict the optimal size of farm enterprises (i.e., the farm size level that minimizes the average total cost of production).

Under assumptions of cost-neutral adaptation, competitive markets, technological divisibility, and absence of risk, taxes, and inflation, the traditional neoclassical theory predicts a clear and simple explanation of the optimal farm size. A one-product farm enterprise that faces a U-shaped average cost function should increase its production, respectively, its size, until its marginal cost of production equals the market price of the agricultural good produced (Varian, 2005; Pindyck and Rubinfeld, 2001; Mankiw and Taylor, 2012; Dabbert and Braun, 2012; Brandes and Odening; 1992).

Nevertheless, when employed for understanding and predicting the growth of (farm) businesses, this approach has been long discussed and criticized in the agricultural economics discipline. For the neoclassical theory, the course of the long-run average cost curve typically follows a U-shaped course. This course is due to increasing, constant, and decreasing returns of scales, correspondingly, at small, medium, and large enterprise sizes. However, the average cost curves that result from farming activities are usually L-shaped. The average cost curve's L-shaped course arises due to the so-called utilization-degressions in costs (*Beschäftigungsdegression*). The utilization-degressions in costs result from increased per-hectare cost efficiencies achieved at larger farm sizes than at smaller ones due to fixed costs distributed over a larger worked area (Weinschenk 1988; Brandes and Odening, 1992).

There is, however, still a dispute among scientists regarding the descriptions of the average cost curve's shape at large farm sizes (Dabbert and Braun, 2012). It is not always clear under which circumstances very large farms exhibit increases in average costs due to, for example, organizational or transport costs and under different specialization courses. Further relevant criticism in the employment of the neoclassical approach for understanding the optimal size and growth in farm enterprises points to the static nature of its propositions (neglect the time dimension, e.g., the transition from one equilibrium state to another one), the non-consideration of risk, and the assumption of the existence of a continuum of technological opportunities.

The traditional neoclassical theory does not satisfactorily explain why historically sub-optimal farm structures are found in real farming, for example, as in middle and west Europe (Weinschenk 1988, Schmitt, 1988). The static approach to farm growth does not consider crucial real-world farming characteristics, particularly time adaptations, technological progress, and path dependency (Dabbert and Braun, 2012; Brandes and Odening, 1992).

Another relevant approach proposed to analyze growth in farm sizes and the determinants of the optimal farm size in agriculture is the one of Schmitt (1988). This author proposes a theoretical model in which farmers behave under rationality principles, aim to maximize the household income, and the optimal farm size is the one that allows an income level that a farm must have in order to be run as a full-time farm (Schmitt, 1988; Weinschenk, 1988; Balmann, 1994). Moreover, the work of Schmitt (1988) indicates that the optimal farm size is to be defined as such at the point in which the production factors used in the farm achieve a marginal revenue that they could also achieve when used outside the farm (Schmitt, 1988). This approach proposed by Schmitt has been, nevertheless, debated. Weinschenk (1988) argues that Schmitt confuses the question of optimal farm size with the question of optimal use of family labor; according to Weinschenk (1988), the question of optimal factor use can be answered with the postulates of the traditional marginal theory and that answering this question does not provide insights that explain the reaching of optimal farm size.

The field of Evolutionary Economics has proved to be fruitful in providing concepts and approaches that help to improve the understanding of particularities of agricultural production (Berger and Brandes, 1998). This theoretical body's primary focus is on the temporal adaptation process; it is considered that observed economic outcomes are related to –and can be explained by– origin conditions. Path dependence and a micro foundation approach to the representation of individual behavior play a major role. It is further assumed that the units of study (e.g., agents, farmers, actors) do not possess a full understanding of their environment and its future developments; instead, adaptation and discovering are typical behaviors of the study elements. Under the perspective of Evolutionary Economics, agricultural structural change can be understood as the collective result of unbalanced interactions of growth and contraction among actors that have heterogeneous learning pathways (Berger and Brandes, 1998; Berger, 2004).

Brandes and Odening (1992) incorporate several elements of the Evolutionary Economics perspective in the presentation of a dynamic approach for a better understanding of growth and contraction in agriculture. The authors suggest that the realized and expected technological progress, the existence of sunk costs in already-realized investments, and the rentability of expected investments belong to objective factors of a dynamic approach for explaining farm growth. Additionally, subjective factors are time preferences and risk aversion, which depend on individual farmer characteristics.

The existence of realized and expected technological progress suggests that the process of farm growth towards an optimal farm size has to be seen as a continually moving goal. Given that technological progress regularly shifts the average cost curves towards lower levels, one can no longer expect a single and unique optimal farm size (like proposed by a static approach to farm growth), but rather several bigger optimal farm sizes that increase with time as technology develops (better and bigger machinery, better methods of production).

Furthermore, the existence of sunk costs in already-realized investments plays a role in the degree of incentives to grow; farms with older investments/facilities have relatively higher incentives to grow compared to farms with newer and more expensive investments and facilities. Given that much of the investment value in farm facilities or agricultural technology can be considered a sunk cost, farms with older facilities have less value to lose than farms with higher-value investments whenever a takeover of more modern, growth-oriented technology over the selling of the old one is planned.

Also, the rentability of expected investments is a relevant factor that determines farm growth. Brandes and Odening (1992) continue explaining that farm growth can be expected particularly in convenient locations, e.g., where the land markets allow land acquisition at favorable prices, and the soil quality allows good land productivity. The land market is one crucial factor for farm growth, given that it drives the dynamics of structural change by allowing the transfer of land from exiting farms towards growth-oriented ones (Huettel and Margarian, 2009; Kellerman et al., 2008). However, the availability and conditions that determine the acquisition of liquidity to perform the necessary investments for growth, which typically come in the form of credit, can prevent growth-oriented farmers from realizing their expansion. For example, farmers with high shares of rented land may not have an adequate asset base for receiving a credit even at large farm sizes. On the other hand, and especially in cases of dependence on external financing possibilities, the expected risk of planned investments plays a role in the incentives to grow given that the acquisition of appropriate levels of credit can endanger the existence of the farm whenever volatility in prices or yields is present.

Subjective factors such as time preference and the risk aversion level of the farm manager can also define the incentives to increase the farm size. Brandes and Odening (1992) point out that lower time preferences can result in more substantial incentives towards farm growth; this is because farm managers with a higher time preference are less inclined to shift consumption needs to the future. The authors suggest that young farmers (for the European context) are more inclined to have lower time preferences and, therefore, to show a stronger growth-oriented behavior due to the relatively higher valuation of future utility towards current utility. Moreover, a higher less aversion can result in a more dynamic path towards farm growth, yet, a higher degree of risk comes typically with higher probabilities of failure, which leads to no clear propositions towards the effect of risk aversion on-farm growth.

From a dynamic point of view, it can be summarized that the optimal farm size is one where the realized investment levels allow that current and future (increasing) consumption needs of all household members are satisfactorily covered and that it further allows for investment levels that facilitate the transition from one technological level to a new one (Dabbert and Braun, 2012; Brandes and Odening; 1992). Moreover, a closer understanding of the farm size structure of a region should, together with the determinants mentioned above, consider the role of path-dependence. Changes from one state to another imply that costs are incurred and, typically, the shift from one farm size structure to a new one requires that organizational and learning skills need to be acquired. Path dependence is one relevant factor that explains why it is not typical to find a farm structure of big farms in Southwest Germany, whereas the opposite is to be found in East Germany; farm size structures are influenced by the historical trend and initial farm structures (Zimmerman and Heckelei, 2008).

Nevertheless, some authors suggest that farm growth can not be explained by past events (i.e., path dependence). An alternative view for understanding the rate of farm growth was proposed by Gibrat (1931) with his Law of Proportionate Effects (Gibrat's law). This approach suggests that the growth rate of (agricultural) firms is exogenous to their initial size and that growth results from a random process. This stochastic process generates theoretical farm size distributions (log-normal) similar to the distribution of the farm sizes observed in reality (Kostov et al., 2006). Many authors use this approach as a starting point for empirical analysis of farm growth (Weiss, 1999). However, empirical studies have found a range of factors that systematically can explain farm growth without the assumptions of stochastic farm growth processes.

The crossing from a static approach towards the dynamic approach for understanding optimal farm sizes and the incentives towards farm growth has been founded in the criticism that the static neoclassical approach receives by constructing its propositions based on assumptions considered "unrealistic". The modification of the static theory with the inclusion of more realistic propositions (derived, for example, from other fields of study such as psychology or Evolutionary Economics) results in theory with new quality; while it is possible to deduce the effects of changes in parameters and variables on outcomes (e.g., farm sizes, equilibrium) in the context of the traditional neoclassical theory, a modified, more realistic theory does not always allow such deduction (Brandes, 1985). The modified, dynamic approach for understanding farm sizes and growth does not unambiguously allow to predict how a given farm enterprise will react towards changes in the environment; nevertheless, it allows to understand the reasons why a given state of nature can differ from the profit maximization state (Brandes, 1985).

2.2.3 Growth and contraction: Why do farmers exit and others grow? Empirical evidence

Pre-considerations

This section summarizes relevant empirical research that addresses the determinants and dynamics of agricultural structural change. The presentation is shown with a focus on European experiences and, in some cases, other industrialized regions (e.g., Canada). The presentation highlights the methods used in the empirical treatment of structural change and the deduced determinants of the structual change process.

Empirical evidence

Zimmermann et al. (2009) present a literature review on the empirical treatment of agricultural structural change. The authors show that econometric analysis (e.g., regression analysis), Markov chain models, and simulation models (e.g., agent-based models) are common methods used for predicting changes in the farm structure of a region. Moreover, the authors emphasize the advantages and disadvantages resulting from the use of Markov chain models and agent-based models and conclude that it exists great variety in the number of relevant drivers of structural change since these depend on the scope of the analysis to be made and the characteristics of the studied regions. In this review, various studies making use of these approaches are presented and highlighted together with their main conclusions and insights.

From a specific point of view, Weinschenk (1988) argues that, historically, the changes in the size of the farms in the European countries have been more influenced by inheritance dynamics and political factors rather than by changes in the underlying economic conditions. With a focus on the relationship between inheritance dynamics and structural change, Troost and Berger (2016) show that modeling farms in Southwest Germany as family farms lead to much higher farm exit rates than modeling them as standard firms with an unlimited investment horizon. The authors show that robust differences arise in investments in biogas plants, silage maize area, and participation in agri-environmental schemas when distinguishing between family and non-family farms. The authors employ a whole-farm mathematical programming model implemented in the agent-based model MPMAS (Schreinemachers and Berger, 2011) that represents production and investment decisions that take into account relevant organizational characteristics of family farms.

Huber et al. (2015) provides further empirical contributions addressing agricultural structural change. The authors analyze farm growth dynamics of farmers in Central Switzerland. By using survey data from two cantons of Central Switzerland and census data from the Federal Office for Agriculture in Switzerland, the authors estimate and determine decisive variables associated with farmers' intentions to choose among strategies of growth. The authors indicate that farm growth intentions are primarily determined by structural characteristics such as a relative change in farm size in the past, current farm size, and sunk costs. Moreover, young farmers seem to be more likely to show a more growth-oriented behavior; their results are consistent with the theoretical postulates provided by the dynamic approach proposed by Brandes and Odening (1992). Moreover, it was identified that a limited availability of labor does not seem to be a direct factor that constraints the growth intentions in this case study.

Happe et al. (2009) provide an analysis for Slovakia. The authors study the economic and non-economic reasons for farm exit employing the agent-based model AgriPoliS (Kellermann et al., 2008). The authors investigate the dynamics of exit and entry of single-holder farms (non-corporate farms) under the European Common Agricultural Policy (CAP) with a dualistic farm structure employing scenario analysis. In terms of regional development, the authors indicate that the single area payment scheme (in the context of the CAP of the European Union) provided to farms led to single-holder farms to remain in agricultural production and to incentive potential farm successors to enter. The authors point out that their simulations highlight the importance of framework (support) conditions in preserving the agricultural farm size structure in their studied case.

With the focus on an extended period of analysis (1960-2000), Freeman et al. (2009) analyze the evolution of farm sizes in Canada using a model implemented in the agent-based software NetLogo (Wilensky, 1999). The authors represented farmers of a typical grain and oilseed region of the Canadian prairies in 1960. The modeled farms were constructed as growth-oriented farmers (they all wish to acquire more land), and farmers are distinctively endowed with risk aversion levels. The authors conclude that farms with an initial farm size larger than the average farm size are more likely to remain in farming and grow. In contrast, smaller farms are more prone to exit farming in prolonged economic downturns. The authors attribute this result to the relatively higher difficulty of small farms to generate enough liquidity that allows them to deal with the farm household's consumption needs and produce a satisfactory asset base and associated creditworthiness that allows them to jump to a higher farm size level. Besides, the authors show that the income that derives from stabilization and support programs transfers contributes to a slow down of the exit rate and the preservation of the farm structure. Finally, the authors argue, in coherence with the perspective of Schreinemachers and Berger (2011), that agent-based simulations are an adequate approach for assessing the effects of policy in farming and for the analysis of farm structure and structural change given the nature of the method for allowing the design and implementation of dynamic market interaction between several heterogeneous modeled farms.

With a panel database of more than 50,000 Austrian farm households for three years (1980, 1985, and 1990) in Upper Austria, Weiss (1999) performs an econometric analysis to estimate the impact of farm-specific characteristics on-farm growth and survival. The author shows evidence of polarization on-farm growth: Small farms seem to grow fast towards a specific minimum efficient scale of production, yet, larger farms can reach a (larger) efficient minimum scale of production. The results of Weiss (1999) also suggest that initial farm size does significantly determines the degree of farm growth and survival; from his results, an increase in initial farm size by one standard deviation from the sample mean increases the probability of survival by 5.49 percent. These results do not support the Gibrat's law for the Upper Austria case.

Huettel et al. (2011) investigate the relationship between farm growth, farm exists, and the land market's role in explaining the different patterns of structural change among distinctive regions in Germany. The authors use farm-level data from the agricultural census for the West German agricultural sector for the years 1999, 2003, and 2007 to estimate a generalized linear model for predicting the impact of inequality of land distribution among regions on the share of existing and shrinking farms. The authors argue that the exit rate of farms is higher in regions where asymmetries in the land distribution are also higher. Furthermore, and by utilizing a theoretical model of structural change, these authors suggest that large farms are expected to grow faster than small farms. This result is based on the assumption of cost advantages for farms with larger farm sizes.

The lessons from the results of Huettel et al. (2011) are coherent with the ones derived from the investigation made for Canada by Freeman et al. (2009), yet, the potential effects of sunk costs may be neglected when evaluating the incentives to grow at different initial evaluated farm sizes. As presented above (see theoretical section), differences in sunk costs can play an important role in shaping the incentives of farm managers to expand. In a related contribution, Huettel and Margarian (2009) make use of a Markov chain and a multinomial model to analyze farm growth, decline, and exit in the West German agricultural sector using data from the agricultural census for the years 1999, 2003, and 2007. The authors show that trends of higher land concentration at the regional level are associated with expansion of large farms, on the one hand, and farm closures and possible part-time farming, on the other.

Another contribution that investigates the dynamics of structural change is the one of Happe et al. (2008). The authors analyze the effect of the European Union income support policy of farm-direct payments schema on structural change. The authors use the agent-based model AgriPoliS and analyze two regions with different farm structures in Germany. The authors show that farm average farm sizes in the studied regions are sensitive to decoupling direct farm payments (independent income support) from production and that these decoupled support policy might strengthen the incentives to exit the farm business given that small farms might find profitable to receive the income support and then exit farming. Moreover, from the simulation results of this study, the authors argue that independent income support to farms might benefit unprofitable farms by providing them with incentives to leave the sector, and it may also benefit growth-oriented farms since they could acquire the land of exiting farm managers.

2.2.4 Technological innovations and their relation to the definition of economies of size in agriculture

The review of the theoretical and empirical literature presented in the previous section revealed that one particular factor has a significant effect on farm growth, and hence, serves as a trigger for structural change: Technological progress. Apart from innovations in seed improvements and management techniques, the adoption of technology in the form of mechanization was mainly responsible for the drastic reduction in the number of farms in industrialized countries, contributing to accelerating structural change in agriculture (Schmitz et al., 2014). Several aspects related to the relationship between machinery use and farm growth require consideration.

The relationship between farm growth incentives and machinery use can be narrowed down to the treatment of course of the costs per hectare. While expanding production (e.g., through an increase in the land under cultivation), the *absolute* variable costs derived from machinery use typically grow at a constant rate. This constant growth rate, in turn, results in *per hectare* variable costs (average variable cost) that are constant; working one additional unit of land (one more hectare) with a specific technological aggregate (i.e., an implement and a tractor) should cost always the same because a fieldwork operation on the the first hectare requires the same resources (e.g., time, fuel) like on a second, third or fourth hectare if the same technological aggregate is employed in the absence of shape differences in the plots. This example shows the non-existence of declining marginal product derived from machinery services per hectare or hour.

Nonetheless, the farm's average fixed costs (fixed cost per hectare) tend to *decrease* as more hectares are serviced due to the distribution of fixed costs among more hectares. Given that the average total cost is the sum of average fixed costs and average variable costs, performing fieldwork operations on more hectares should result in reduced (total) average cost (Kay et al., 2004). This existence of utilization-degressions in average cost curves while expanding the level production together with technological driven procedural-degressions (i.e., the transition to a more efficient process if economically attractive with increasing production volume - *Verfahrensdegression*) are two responsible factors for increasing the incentives of farmers increase production –respectively, the agriculturally used area (Brandes and Odening, 1992).

The existence of (long-run) decreasing average cost curves is referred to in the economic literature as economies of size. Farms of a specific size that face decreasing long-run average cost have incentives to get larger since production gets cheaper by growing. Theoretically, it is also possible that after a farm reaches any given size, the long-run average costs stop decreasing, and even at even larger farm production levels (together with the corresponding increase in farm size), average costs increase. An upward trending long-run average cost curve corresponds to a situation of diseconomies of size (Pindyck and Rubinfeld, 2001; Mankiw and Taylor, 2012; Dabbert and Braun, 2012; Kay et al., 2004).

Empirical investigations on the nature of average cost curves in agriculture suggest the existence of economies of size, at least at an initial size range (Duffy, 2009; Kay et al., 2004). In Germany, for instance, Happe et al., (2008) argue that farm growth most often takes place via the exploitation of economies of size. For the study case of Niedersachsen, in West Germany, Johnston and Bischoff (1977) showed evidence of the existence of economies of size among specialized sugar beet and grain farms up until the range of 200-300 hectares. Yet, beyond this initial range of achievement of economies of size, average cost curves tend to remain constant for subsequent size levels, in a way that many several farms with different farm sizes can coexist and face the same average cost of production, a further upward trend of the long-run average cost curves has not yet conclusively observed (Dabbert and Braun, 2012).

2.2.5 Relationship between indivisibilities, full use of acquired resources, farm machinery management and economies of size

Many factors have been identified as sources of economies of size. The availability of new lumpy technologies is one fundamental source of economies of size. New farm technology is often expensive, and in order to acquire and make efficient use of it, a minimum utilization level is often expected (Ray, 1998). In terms of farm machinery and similar indivisible technologies, the minimum use level is usually represented by a minimum of hours used or hectares serviced. Besides, bulk purchases of inputs that lead to price discounts, market power conditions, or positions where farmers can achieve price premiums due to the delivery of large volumes of products have also been identified as alternative sources of economies of size in agriculture (Kay et al., 2004; Duffy, 2009).

In contrast, the existence of diseconomies of size is commonly attributed to difficulties in the management capacity as the farm business becomes larger. Additionally, increasing farm size can lead to increases in the costs to supervise labor, which can further lead to increasing average cost curves as farms get larger. Farms with animal production orientations that want to increase their herd sizes can face higher additional costs due to odor and manure disposal regulations; these regulations often force farmers to access land located far away. In particular, internal transport costs among the most significant reasons resulting in diseconomies of size in the agricultural sector (Weinschenck, 1989). This last observation shows the importance of land fragmentation on the cost structure of a farm.

Land fragmentation has been defined as the condition in which a farm performs production activities on numerous spatially-separated parcels of different shapes and sizes (Van Dijk 2003, 2014). In the European Union, land fragmentation has the disadvantage that it can potentially hinder mechanization strategies, causes inefficiencies in production, and, consequently, can reduce farmers' achievable income (Demetriu, 2014).

2.2.6 Utilization degree of farm resources and economies of size

Decisions on technological use and acquisition play a crucial role in the formation of the cost structure. In particular, the technology selection and acquisition in the form of farm machinery and equipment has been acknowledged as one of the most difficult problems in farm management (Søgaard and Sørensen, 2004), and in order to maintain competitiveness and rentability, farmers are expected to select an optimal machinery and equipment portfolio. One fundamental factor responsible for generating economies of size is the full use of available lumpy technologies; these technologies, when purchased, are non-divisible and generate fixed costs that need to be paid regardless of their usage. Making full use of, for example, particular farm equipment should result in lower total average costs (variable and fixed costs per hectare) than the usage of, say, 50 percent of the full capacity of the same equipment. For farm machinery technology, adequate and efficient machinery management that allows farmers to acquire and use the proper technological capacity for field operations in the available time windows is critical for maintaining the business competitiveness, especially when farm managers expand their production level.

2.2.7 Alternatives to acquire adequate capacity for field work operations: hiring, renting, leasing and sharing farm machinery and equipment

The majority of farm managers show preferences for buying and owning their farm equipment. Owned equipment and machinery provides full control over the use and disposal of the technology; it also provides pride. Many farmers take pride in owning new technologies for farming and might even be willing to accept higher long-run costs (Edwards, 2019; Kay et al., 2004) provided that the pride of having the equipment results in a utility prime. Nevertheless, farm machinery investments represent a large and significant use of the farm's resources. When the investment capital is limited, financing options are expensive, or credit markets are non-existence, machinery investments can be reduced by utilizing ownership alternatives. These alternatives typically manifest in the form of rental, leasing, or custom hiring (Kime et al., 2014; Kay et al., 2004). Besides, purchasing used machinery or sharing investments and entering in cooperation agreements for machinery acquisition are alternatives ways of acquiring the adequate equipment capacity to perform field operations.

The following table below provides an overview of the functioning of the different relevant alternatives for the acquisition of farm machinery and equipment capacity as well as the advantages and recommended appropriate use of these alternatives (based on Kay et al., 2004; Kime et al., 2014).

1. Rental contracts:
   (a) Functioning:
      i. Rental arrangements typically involve the use of equipment or machinery between couple of days to a maximum of a whole season. The user usually pays a fixed rental fee and the cost of the insurance and mantainance but is not obligated to pay for repairs. Rental options are considered to be short- to medium term commitments that are backed up by a formal contract between the rental provider and the farm manager.
   (b) Advantages and use:
      i. Renting equipment is appropiate when farm managers i) are constrainted in the amount of investment capital available, ii) or the options for financing are scarce and expensive, iii) there is a need a specialized piece of equipment for a specific field operation, iv) or a need extra field work capacity for a short to time, v) or the manager has interest in trying out a new type of equipment without fixing resources for a long time frame by investing in the technology.
2. Leasing:
   (a) Functioning:
      i. Leasing equipment is a middle to long term contract and requires the definition of a contract between the dealer or leasing company (lessor) and the farmer manager (lessee). The lessor grants control of the equipment to the lessee in exchange of a periodic lease payment. At the end of the

contract it is common that the lessor allows the lessee the option to buy the equipment at an approximate market value of the equipment.

(b) Advantages and use:

i. Leasing allows farmers to get equipment with the new technology without making actual investments in equipment that will eventually become obsolete. The lease reduces the risk of obsolescence given that the lessee is not obligated to keep the equipment at the end of the contract. Many farm managers typically lease for a couple of years and then exchange the equipment for a new one with a new contract.

3. Custom hire:

(a) Functioning:

i. Custom hire refers to the capacity of the farm manager to hire a specific fieldwork operation. For machines or equipment that are expected to be used at a low utilization rates it is often more economical to hire the work. Hiring field work operations usually requires the payment of a fixed rate per acre, hour or ton. In terms of labor provision, the custom operator typically supplies the necessary labor to operate the machinery that performs the fieldwork operation.

(b) Advantages and use:

i. Custom hire is appropiate when low levels of use of a machinery are expected (owning an equipment for low utilization rates results in payments of fixed costs that are spread over a limited amount of hours of use or hectares worked). At higher levels of use the decreases of fixed costs on owned machinery usually makes that fieldwork operations over custom hire become economically viable as the ownership costs (depreciation, insurance, etc.) are spreaded over more hectares or hours used. Whenever custom hiring services are acquired, the labor provision of the custom operator frees the farm operator's available labor. This reduces the preassure to hire labor or if the farm manager faces a high opportunity cost of its own labor. Custom hiring is also an important alternative whenever the farm manager lacks particular skills of specialized field operations; custom operators are typically specialized in their offers and this provides advantages in their performance of some field work operations.

In regions where small farm structures prevail, as in Southwest Germany (Happe et al., 2008), the constant advances in farm technology – which are oriented towards higher machinery hectare and use efficiency – can often lead to situations where machinery and equipment are far from being fully utilized. In these contexts, owning a piece of full equipment does not result in the most profitable approach for the farm manager, and custom hire, renting, or leasing represent profitable options. Besides these alternatives, cooperation agreements are a frequent practice among farmers for acquiring adequate equipment capacity to perform field operations. Cooperation agreements for joint investments have the objective of improving income and reducing costs by achieving degression effects in the use of labor and capital (e.g., equipment) and improved farm machinery management (Doluschitz et al., 2011).

Cooperation arrangements in agriculture can be distinguished by their degrees of attachment between farms. Doluschitz et al. (2011) determine four different attachment levels. At the first level, cooperation can take place in a broad sense, where farmers gather intending to increase presence and achieve objectives such as the strengthening of the market position, examples of these types of cooperation agreements are producer organizations (e.g., *Deutscher Bauernverband*). At the second level of cooperation, the attachment level increases, and this form of arrangement is characterized by farmers making joint use of production capacities (e.g., machinery and equipment). A higher degree of attachment is achieved at the third level of cooperation agreement where farmers can work together in a main determinate activity (e.g., production of bioenergy), and the rest of the farm activities of the corresponding members remain in their individual decision-making process. Finally, the highest form of attachment corresponds to a fusion, where two or more farms merge, and, at this point, they are no longer considered as several units but as a unique larger farm unit.

For the acquisition of the appropriate farm machinery and equipment capacity, farmers often engage in arrangements for the shared capacity of factors of production (level two of attachment). Doluschitz (2017) recognizes two platforms at which these arrangements can take place: Machinery associations or cooperations (*Maschinengemeinschaften*) and machinery rings (*Maschinenringe*). Machinery rings are self-help associations of farmers that are regionally organized. These are associations of farmers, which serve for the inter-business use of machines in individual ownership to increase their degree of utilization (Doluschitz et al., 2011). Through the coordination and implementation of the use of machines among several farm businesses, the machinery rings allow their members the possibility to apply new technologies in their businesses and take part in technical progress without having to take the risk of expensive investments (Maschinenring Rottahlmuenster, 2020). Machinery rings are usually conformed by a high number of members (e.g., 1300 farmers) and represent a legally registered association (e.g., e.V. and GmbH) with a defined organizational structure and farmer support procedures.

Machinery associations refer to an alternative to machinery rings for the acquisition of farm equipment capacity. In a machinery association, machines and pieces of equipment are bought, held, and used (shared) by several farmers together (usually a reduced number of farmers, e.g., 2-10). Participation in machinery associations allows increasing the number of hectares serviced by the shared machinery or equipment while reducing average costs associated with using the technology. Additionally, there is no obligation of establishing a legal registration, yet, it is expected that among the farmers that enter in cooperation, contracts and rules are defined in respect to the share of use of the shared equipment and the obligations of the members (Artz et al., 2010; Artz and Naeve, 2016). Usual types of equipment that are bought and shared by farmers in machinery associations are harvest and seeding equipment, fertilizer and-or compost spreaders. Nevertheless, this type of cooperation arrangement requires coordination among participating farmers in cases where the machinery shared requires use in similar time windows (Doluschitz et al., 2011; Agrarheute, 2013).

The experiences of successful machinery rings in Germany are plentiful, and documentation about these experiences is typically gathered and made available in each machinery ring's specific web pages. In the case of farmers' machinery associations, access to the information about the functioning, benefits, and challenges is limited, since this type of associations are more informal and require that the members of the machinery association voluntarily and openly express their experiences about their particular cooperation arrangement.

2.3 Farm machinery management and climate

2.3.1 Pathways in which climate affects farm machinery management

Many factors determine an adequate and efficient farm machinery management. This endeavor's goal relies on acquiring the proper size and type of equipment to perform field operations at the right times and at the lowest cost possible. In this context, making the right decisions for optimal machinery management is a process that is not independent of weather conditions.

The majority of the fieldwork operations are time-sensitive; this means that they need to be realized at specific plant development stages while considering the appropriate weather conditions for the corresponding field operations. Most of the fieldwork operations depend on adequate weather and soil conditions suitable for utilizing machinery and equipment; some examples are harvesting cereals, grass-hay preparation, and seeding. Cereal harvest requires low humidity, grass-hay preparation requires persistence of dry conditions over several days, and wheat seeding requires specific temperature and soil moisture for optimal germination and growth.

Besides, the field operations that need to be realized at the specific stages of the plant development are generally constrained by the availability days suitable for the farm manager to make use of its equipment. The weather-dependency of the fieldwork operations and the derived effects on the optimal choice for the size of equipment are exemplified and illustrated by the following experiences of farmers in Mecklenburg-Vorpommern and U.S. Midwest correspondingly:

> "*We have the disadvantage [...] that our harvest window is a bit later than in the whole of Germany, central Germany, and of course the risk increases on rainy days, and therefore the demand for larger harvesting technology is always there to get in even faster to harvest these good qualities and quantities in this small harvest window*" (Taken from: Welt Nachritchten - Carsten Stegelmann, Mecklenburg-Vorpommern, 2020. Own translation)

> "*Because of climate change you are buying bigger machinery. You are doing stuff in a hurry. Ha, you're spraying in two days what used to take two weeks. You're combining in three days what used to be three weeks.*" (Taken from: Doll et al., 2017)

In order to acquire the proper machinery and equipment for the performance of fieldwork operations, farmers need to consider the available days they will have at disposal in order to perform the specific works at the different stages of the plant growth. In this context, the first factor to consider in the acquisition of farm machinery and equipment is the field capacity. The field capacity indicates the number of units of area (acres, hectares, manzanas, etc.,) that can be worked per hour for a given equipment characteristic. Calculating the (theoretical) field capacity (FC) of the equipment is done by considering the speed of the machinery, its width, and a degree of efficiency (ef):

$$FC = \frac{speed * width * ef}{\gamma} \tag{2.1}$$

where the efficiency factor corresponds to the recognition that many types of machinery and equipment are not always used at their full capacity (due to work overlap, turning times, lubricating, handling materials, refill of inputs). The factor γ is a measure that adjusts the calculation for an adequate capturing of the full operating width of the machine that is being used. By calculating the field capacity of machinery, it is possible to obtain the field-day requirement for the performance of a specific field operation. The calculation of the field-day requirement (FDR) involves the hours per day that the equipment can be used, the estimation of the theoretical field capacity and the number of area units to cover (Hanna, 2016; Kay et al., 2004):

$$FDR = \frac{Area}{Hours_{Day} * FC} \tag{2.2}$$

from the above-shown formula of field-day requirements, it is possible to establish a direct relationship between climatic conditions and their effect on farm machinery management: The availability of suitable days for performing a particular field operation influences the decision of the farm manager on the level of use of the three variables that the farm manager can control. Everything else constant, fewer available suitable days for field operations can be faced either with reductions of the area to be serviced (reduction of the field day requirements), increases in the per-day use of particular equipment (which additionally involves the corresponding adequate supply of labor capacity), or increases in the field capacity (reduction of the field day requirements). This last factor ultimately depends on either increase in the efficiency of the equipment or in the acquisition of wider/larger machinery and equipment. These values are usually provided by extension offices and serve as reference parameters for the performance of fieldwork operations, in Germany, the information derived from these types of calculations can be obtained from institutions such as the *Kuratorium für Technik und Bauwesen in der Landwirtschaft* e.V. (KTBL); the following subsection shows how this information can be used to obtain insights on achievable working capacities for several field operations.

2.3.2 Field capacity estimates of machinery and equipment portfolio based on KTBL technical coefficients

The *Kuratorium für Technik und Bauwesen in der Landwirtschaft* e.V. (KTBL) in Germany holds a collection of over 5,000 fieldwork processes for a comprehensive selection of fieldwork operations (e.g., plowing, seeding, fertilizing). The fieldwork operations are further sub-divided and distinguished by fieldwork processes or fieldwork activities; each field operation can be effectively performed by using a specific field process/activity. Apart from the type and size of the equipment combination required for a fieldwork process, each process also defines the adequate draft power to be employed (e.g., sowing with a two meters-wide sowing machine and a 120 kW tractor or sowing with a four meters-wide sowing machine and a 233 kW tractor). The information on fieldwork processes is accompanied by information on the machine costs, the diesel demand, and the work time requirements needed for its performance. The information provided is determined considering the following part-times: Primary time, turnaround time, supply time, unavoidable loss time, waiting time, travel time, and set up time. Additionally, the information is distinguished by several sub-tasks (*Teilarbeiten*) that may consist of loading, transporting, unloading, drying, and storing (KTBL, 2020).

Based on the technical coefficients obtained from KTBL, the below-shown figures present relationships between equipment size and achievable working capacity (number of hectares that can be serviced) for several field operations that are suggested by KTBL to be performed on cropping systems with low and plow tillage for conventional winter wheat production. Based on the working time requirements per hectare (*Arbeitszeitbedarf, Akh/ha*) estimated by KTBL for each fieldwork process (e.g., field operation with specific machinery and equipment size), the figures show the extent at which fieldwork can be performed within a half month (assumed of 15 days) at different, exemplary, daily rates of work of the utilized equipment (e.g., 13, 14, 15, 18, 21, 22 hours per day) on work performed in a plot of two hectares size.

Figures 2.1, 2.2, and 2.3 compare several fieldwork operation's capacities to service a determinate range of hectares. For example, the fieldwork operation of plowing with a reversible plow (*Pflügen mit Drehpflug*) exhibits relative low working capacities in comparison to other field operations (e.g., sowing); if a farmer aims to plow and service 250 hectares in 15 days, it has to make use of the biggest equipment for plowing (for which KTBL provides information), in this case, plow with an equipment of 2,1 meters with a use-rate of 22 hours per day. On the other hand, the field operation of sowing with a rotary harrow and seeder (*Säen mit Kreiselegge und Sämaschine*) allows more significant efficiency levels; a fieldwork process that uses the biggest equipment available (4,5 meters) allows the service of more than 400 hectares at the same daily-use rate of 22 hours.

Fieldwork operations for fertilization and plant protection (*Mineraldünger ausbringen, loser Dünger and Pflanzenschutzmassnahme* correspondingly) make use of equipment that reaches larger areas than equipment used for other field operations. For example, the reach of the fertilization equipment can be at the level of 36 meters and 24 meters-wide. Working 15 days with high rates of use per dat of the largest equipment available for fertilization, farmers can service more than 3,000 hectares. On the other hand, farmers can increase the area serviced for plant protection operations by making use of larger equipment that reaches a size of 18 meters, if the farmer wants to achieve a larger area serviced with plant protection, it needs to increase the daily rate of use of equipment of 18 meters wide; utilizing larger equipment on a two-hectare parcel does not result in a higher area serviced. Based on KTBL estimates of working time requirements per hectare (*Arbeitszeitbedarf, Akh/ha*), only by working on a larger parcels it is possible to increase the segment of the curve that shows a positive slope in the width-working capacity curve for plant protection operations.

Figure 2.3 additionally shows the width-working capacity curves for the fieldwork operations of harrowing with seedbed combination (*Eggen mit Saatbettkombination*), harvesting (*Mähdrusch*), seeding with seeding machine (*Säen mit Sämaschine*), stubble cultivators flat and deep (*Stoppelgrubbern flach, tief*), and deep cultivation (*Tiefgrubbern*).

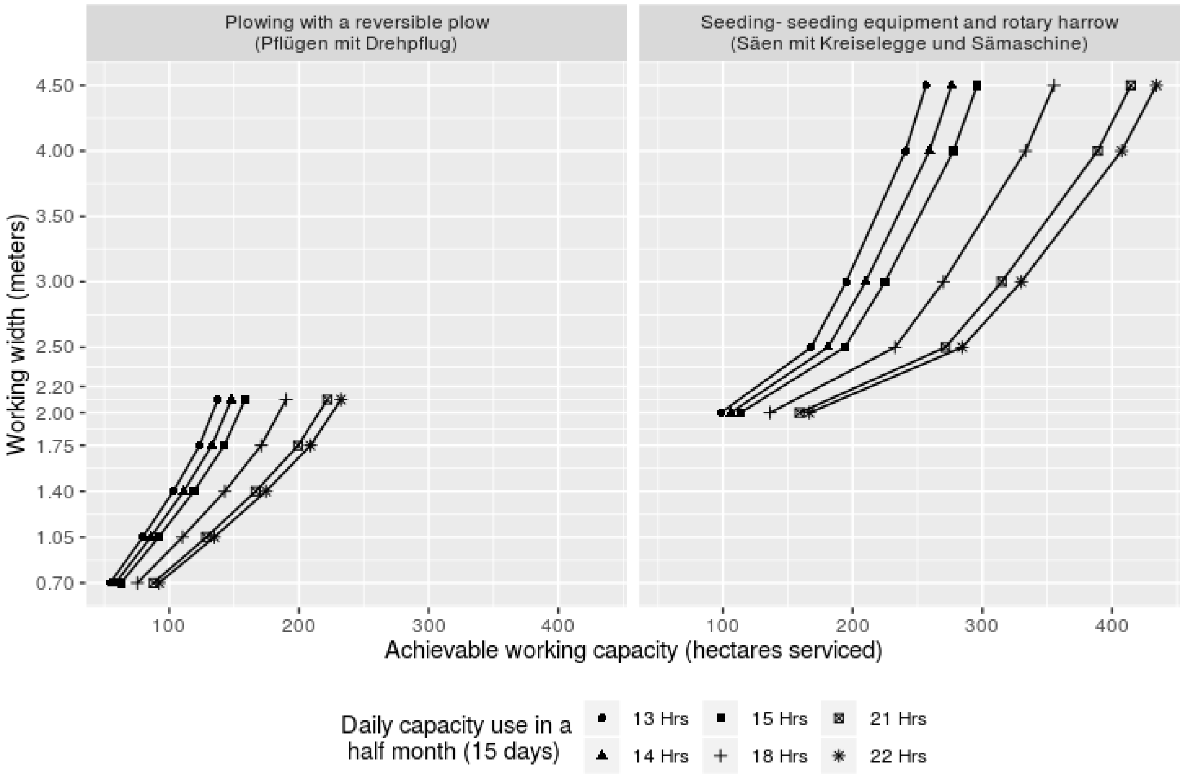

Figure 2.1: *Plowing and seeding achievable working capacities*

All the curves of width-working capacity display positive slopes for all the field operations for all the here considered daily rates of use along the combinations of areas serviced and sizes of the corresponding types of equipment utilized; achieving the service of a larger number of hectares can be realized by correspondingly increasing the size of the equipment used or increasing the daily rate of use of the equipment. These relations are helpful to establish an overview of the width-working capacity curves for several daily rates of utilization over a full half-month for several fieldwork processes. Furthermore, the curves here derived with the KTBL technical coefficients allow determining an overview of the maximum capacity levels of different fieldwork processes for the expected levels of daily utilization. This information becomes relevant to understand the bottlenecks that could arise due to changes in the time windows for performing fieldwork operations for the different crop growth stages and development stages.

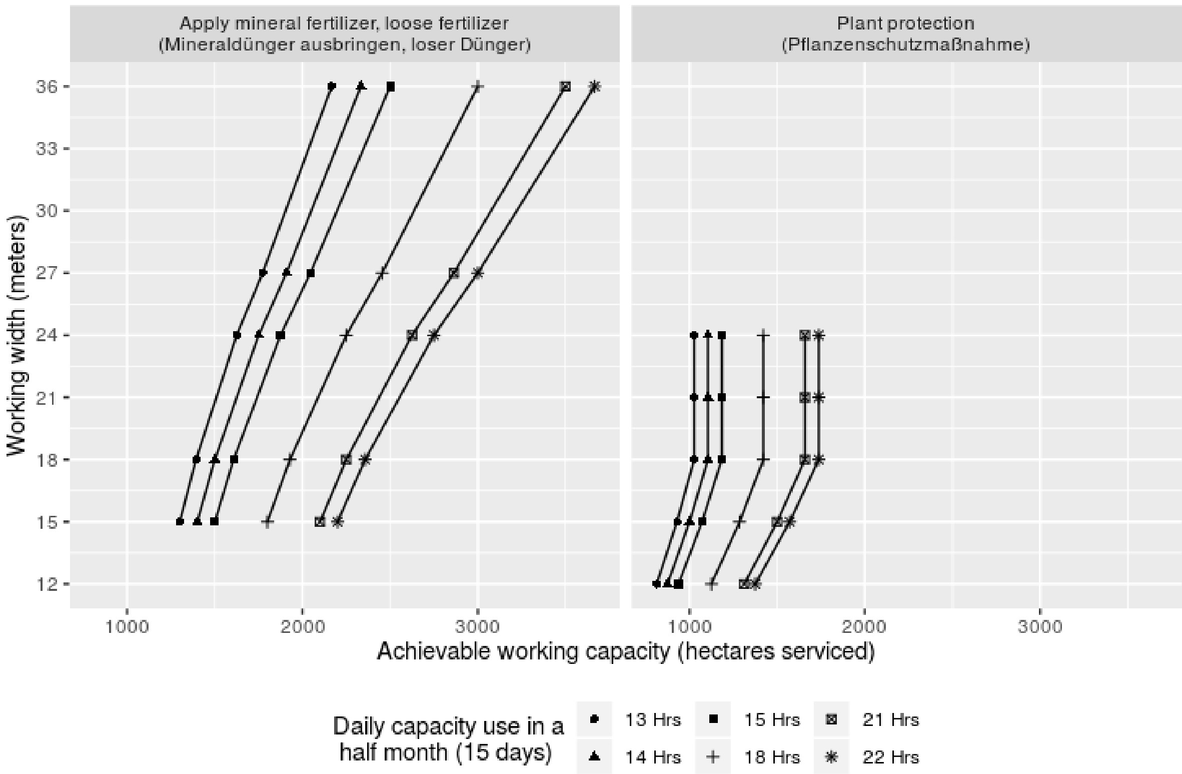

Figure 2.2: *Fertilization and plant protection achievable working capacities*

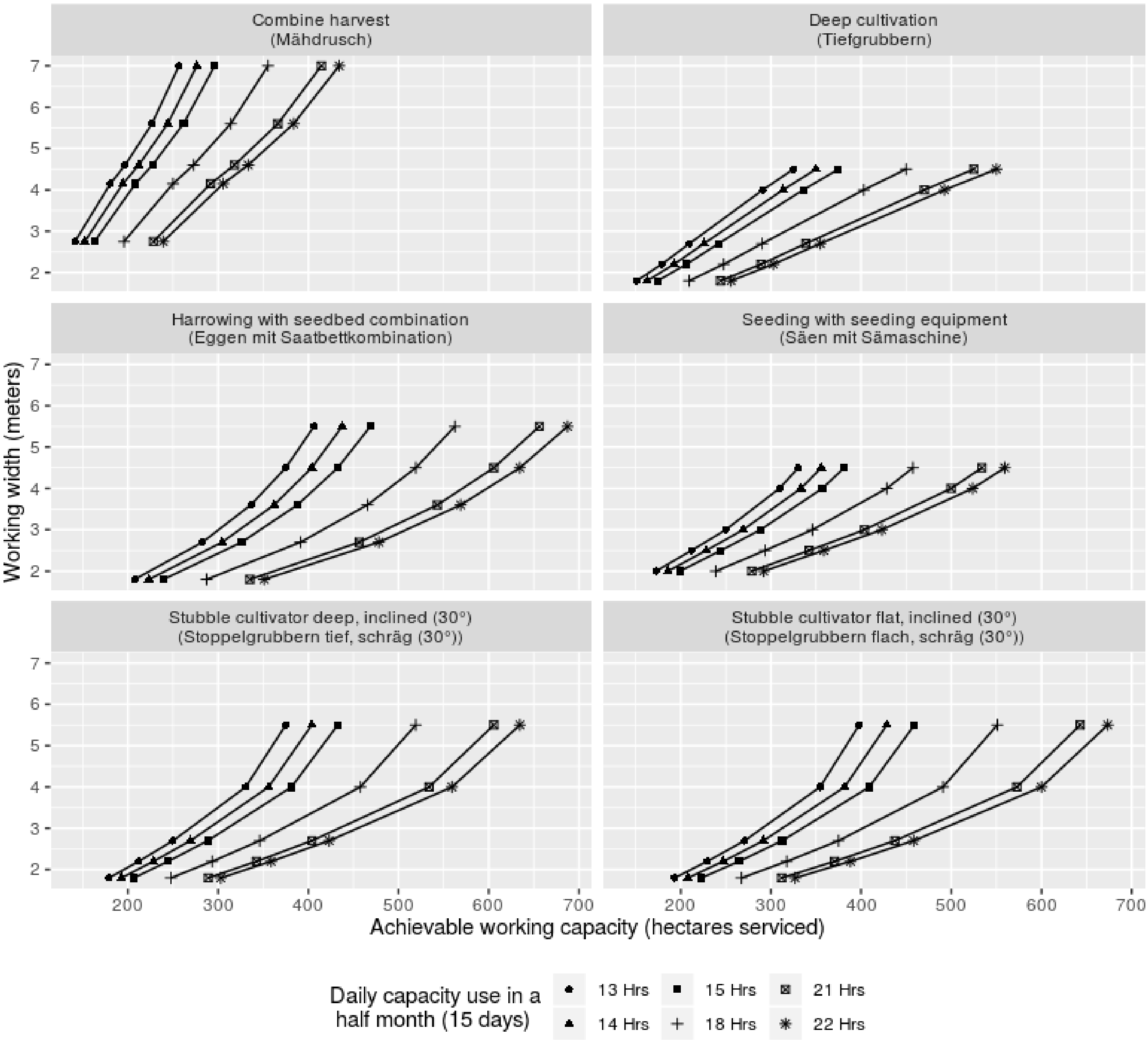

Figure 2.3: *Harvest and soil preparation achievable working capacities*

Chapter 3

Simulation and optimization analysis

Contents

3.1 Dynamic effects of shifts in fieldwork time on land-use and machinery acquisition

3.1.1 Introduction

Farmers' decisions to either exit the farming sector, on the one hand, or reorganize and grow, on the other hand, will inevitably be taken in the context of changed climatic conditions that will manifest due to climate change. Climate change and the uncertainties associated with this process are expected to increase the difficulty of farmers' decision-making regarding the best reorganizational strategy in the process of farm growth. Changes in crop growth and development will have to be faced through adaptations in farm management, e.g., by adapting the timing for fieldwork operations, adapted fertilization operations, or changed plant protection practices if farms aim to achieve the potential yields under new climatic conditions. However, an adaptation of farm management is not only a function of the environment and its effects on plant growth; farm management is additionally dependent on the availability of resources at the farm, together with the complex interactions (e.g., competition) among these resources in the process of achieving specific socioeconomic goals and complying with framework conditions (e.g., long-term profitability, adequate cash flow levels, crop rotation schemes). Farm management decisions can further feedback into the agroecosystem, different cultivation systems can result, for example, in soil erosion and degradation through time, which can further affect future crop management decisions.

The analysis of complex spatial-temporal systems requires a dynamic tool that adequately represents the feedback between farm management decisions, crop growth, and soil processes directly modeled over time. The bioeconomic modeling system MPMAS_XN integrates the agricultural economic agent-based software MPMAS and the plant-soil modeling software Expert-N (XN) into a coupled, parallelized modeling system that runs on High-Performance Computing (HPC) systems (Troost et al., 2020). The model system MPMAS_XN has been applied as a case study to simulate likely farmer adaptations to climate change in the Central Swabian Jura in Southwest Germany (Troost et al., 2020).

Nevertheless, the model system MPMAS_XN has not yet been the subject of sensitivity analysis, nor the processes of the model system have been in detailed examined. The objective of this subchapter is to examine the responsiveness of the model component MPMAS of the model system MPMAS_XN and learn from its sensitivity to several scenarios that represent potential climate change manifestations at the farm level (e.g., yield changes, shifts in the timing of fieldwork operations). The examination in this subchapter is performed for the parametrized recursive-dynamic multiperiod MPMAS model constructed to simulate climate change adaptation in the Central Swabian Jura and presented in Troost et al. (2020).

Why is this type of analysis required, and what is the relevance of the examination performed in this subchapter? Like Berger et al. (2002) manifest for the type of Land Use and Cover Change (LUCC) models – to which MPMAS belongs (Berger and Troost; 2012): Regardless of the model style developed, there is always a risk of building too much complexity into any model, with the result that it is difficult to understand how processes drive emerging outcomes. The emergent outcomes that are characteristic of agent-based simulations can be best understood if the processes the drove them are transparently communicated and assessed. A major challenge that has been identified for limiting the use of LUCC models is effective and convincing communication of agent-based simulation results (Parker et al., 2003). This subchapter aims to contribute in the dealing with these challenges.

3.1.2 Data and Methodology

Study area

The Central Swabian Jura is a low mountainous area (650-850 m.a.s.l.) covering approx. 1,300 square km and located in Southwest Germany. The region is characterized by shallow soils and relatively harsh climatic conditions (mean annual temperatures of around 7 degrees Celsius, mean annual rainfall of between 800 and 1000 mm). Crop production, dairy farming, pig production, and biogas production are major farming activities. Moreover, the majority of the arable farm business engages in the production of spring barley, winter wheat, winter barley, and winter rapeseed. Spelt and oats are also production possibilities. For livestock production, farmers also grow silage maize, clover, and field grass (Troost et al., 2015; Troost, 2014). Additionally, farmers' production decisions have to respect a diverse number of crop rotation restrictions and policy constraints (e.g., manure regulations).

Approach

In this subchapter, long-term recursive dynamic simulations (25 years) are performed to assess the responsiveness of the model component MPMAS of the MPMAS_XN model system to potential manifestations of climate change in the research area of the Central Swabian Jura. The MPMAS model component simulates farm level decisions employing multiperiod mixed-integer mathematical programming (MIP). The long-term simulations are performed by providing user-defined yield courses and ideal dates for the modeled dynamic field operations (seeding, harvesting, fertilizer applications) throughout the simulation periods. The courses of yields and the movement (shifts) of the ideal dates of field operations aim to reflect future responses of these variables due to climate change (e.g., warmer conditions, higher carbon dioxide concentrations). The focus of the assessment is placed on the responses of land-use patterns and machinery equipment acquisition for a farm agent of 150 hectares.

Data

The technical coefficients for the parameterization of the multiperiod programming model were partially obtained from the contribution of Troost (2014) and Troost et al. (2015); these values were compiled based on information of the State Institute for Agriculture, Food and Rural Areas (LEL) (e.g., producer prices), the *Kuratorium für Technik und Bauwesen in der Landwirtschaft* (KTBL) (e.g., for machinery and equipment investment costs, fuel consumption, input costs, and efficiency of fieldwork operations), and the Federal Statistical Office (*destatis*, 2012). Initial yields and optimal dates for fieldwork operations for the crops considered in the MPMAS model component were established based on a general assessment of expert opinions in the context of the research project "Regional Climate Change" (DFG - *Forschergruppe 1695 Regionaler Klimawandel*), statistics by the State Statistical Office of Baden-Württemberg (*Statistisches Landesamt*), and KTBL data.

Model Structure

The MPMAS model structure is described in detail in the documentation section of this thesis in chapter six. Here, an overview of the model structure is presented.

The model component MPMAS of the model system MPMAS_XN was implemented with the same flexible approach for machinery and equipment choice for fieldwork operations proposed by Troost and Berger (2015). The crop-management strategies specify the initial timing and the type of fieldwork operation to be performed, but the farm agent has flexibility in choosing the type of aggregate (i.e., equipment type and tractor) to use for the work. The timing for fieldwork operations was established for a time resolution of half-months. The implementation's novelty of the MPMAS model for the Central Swabian Jura is the treatment of the fieldwork timing. The fieldwork's –expected and effective– ideal timing can shift over time following the results of crop phenology simulated by XN and communicated to MPMAS (in coupled simulations) or in accordance to user-specified trends. Currently, the assessment is made on arable production decisions, yet, the MPMAS model can be extended for consideration of livestock and biogas production. In the simulations here performed, the simulated farm agent form its expectations of yield and fieldwork timing based on the naive expectation formation mechanism $(t-1)$ for the updating of expectations of crops' yields, fieldwork timing, and soil mineral nitrogen contents. Nevertheless, the MPMAS model component offers additional options for capturing expectation formation (e.g., constant, rational, double exponential smoothing).

The crop rotation representation was established following explicit rotation rules obtained from expert interviews recorded by Troost (2014) for the research region of the Central Swabian Jura. The crop rotations were implemented with a spatially and temporally explicit representation to capture and keep track of the characteristics of each cell of the shared map (landscape) to run a complex inter-temporal and coupled model system. This approach allows for more flexible planning that allows for differences in crop shares across the planning horizon and the plot's history. Three types of rotation schemes were considered: i) Direct next-year non-allowance (crop A can not follow crop B), ii) continuously growing classes (i.e., wheat and barley belong to a "cereals" class), where crops belonging to a class can be grown for no more of "n" seasons/years continuously, and iii) rotation rules where a crop can only be grown in a plot if other crops (or the same crop) have been grown with a break of at least "n" years.

The assumed objective in the solution of the decision problem is to maximize the discounted sum of cash withdrawals that agents perform at the beginning of each planning period. Revenues derive from selling crops (winter wheat, winter barley, winter rapeseed, spring barley, and silage maize) and costs derive from payments for inputs, fuel, wages, investment costs (and depreciation of assets). The trade-offs between earlier withdrawals and fewer withdrawals overall are a function of the discount rate (time preference) and is introduced as an uncertain parameter that varies following the Sobol's sampling procedure (Tarantola, 2012).

3.1.3 Experimental Design

To assess the responsiveness of land-use patterns and machinery acquisition outcomes to alternative and potential climate change developments by 2045, six different scenarios (and an additional baseline scenario) were established in the model component MPMAS of the model system MPMAS_XN. The rationale behind these scenarios is described and supported in the following subsection. Furthermore, all the scenarios were simulated with a common Sobol's sequence (Tarantola et al., 2012) of 50 design points for introducing robustness in the results. All the simulations were run with the resources of High Performance Computing (HPC) of the Baden-Württemberg bwHPC computing facility.

Pre-considerations

The scenarios here proposed have the objective to assess the responsiveness of land-use decisions and optimal machinery acquisition to expected –but uncertain– long-term climate change trends. The scenarios were built in the aim to obtain an understanding of the potential ways that a simulated farm agent of 150 hectares may react to the manifestations of climate change at the farm level. The scenarios' results should be understood as likely responses and not as rigid predictions of what will happen in the future.

Concretely, the goal of the experimental design is to assess the sensibility of the socio-economic model component of the MPMAS_XN system to possible patterns of changes in yields and shifts in the ideal dates for fieldwork operations resulting from altered crop's phenological development. Of course, the responses of yields and plant phenological development to climate change have already been examined in the scientific literature through many statistical and theory-based models. Nevertheless, a common feature distinguished from the literature is the variety of predictions and assessments; depending on the studies' assumptions, the research areas, or methods used, it is common to find a broad spectrum of predictions or discourses. The scenario definition was informed by these distinguished discourses and was complemented with the insights obtained from expert opinions. The proposed scenarios represent several examples and positions derived from the consulted opinions and literature. Therefore, it is expected that they represent, to a certain extent, the possible effects of altered yields and ideal fieldwork operation dates at the farm level.

The defined scenarios were constructed as "bundles" of effects. Based on an initially identified discourse of climate change (informed by literature of expert opinion), each scenario simultaneously captures changes in i) yield trends, ii) shifts of the ideal sowing, fertilizing, and harvesting days, iii) different minimum day-gaps between the sowing of winter rapeseed and harvesting winter wheat, and iv) the degree to which silage maize production can be sold in the market. The adequacy of the scenario definition is discussed in the section of "Discussion."

Scenario 1: Positive yield effect

Discourse: In this scenario, it is considered that farming in the research area will mostly profit from the climate change developments in terms of yields. In this scenario, no initial machinery endowment is provided to the farm agent. Effects:

1. The yield of winter wheat shows a certain increase of 15 percent by 2045.
2. The yields of winter barley, spring barley, and rapeseed follow a positive trend of yield increase. Yet, this trend is implemented as an uncertain element in the model system[1]; yield increases by 2045 range between 0 and 15 percent for these crops. Silage maize is assumed to profit from warmer conditions and this is reflected in a positive –uncertain– trend in yield. Silage maize yield increases by 2045 in a range between 0 and 15 percent. Moreover, selling maize can be done up to an uncertain level in the range of 900-1,600 (t).
3. The minimum day gap between the sowing of winter rapeseed and harvesting winter wheat is fixed to six days. With the intialization dates established for all fieldwork operations (documented in chapter six), a minimum day-gap of six days does not allow growing rapeseed after winter wheat.
4. Ideal dates for dynamic fieldwork operations are all set constant.

Scenario 2: Negative yield effect

Discourse: In this scenario, it is considered that farming in the research area will be mostly negatively affected by climate change in terms of yield developments. This, due to the potential effects of, for example, insufficient water supply and early maturity of crops. In this scenario, no initial machinery endowment is provided to the farm agent. Effects:

1. The yield of winter wheat, winter barley, and spring barley show a certain decrease of 14 percent by 2045. The yield of winter rapseed shows an uncertain decrease between 0 and 14 percent by 2045 .
2. Silage maize is assumed to profit from warmer conditions and this is reflected in a positive and uncertain trend in yield. Silage maize yields increase by 2045 in a range between 0 and 15 percent. Selling maize can be done up to an uncertain level in the range of 900-1,600 (t).
3. The minimum day-gap between the sowing of winter rapeseed and harvest of winter wheat is fixed to six days. With the current intialization dates (see documentation in chapter six) a minimum day gap of six days does not allow growing rapeseed after winter wheat.
4. Ideal dates for dynamic fieldwork operations are all set constant.

[1]All the uncertain trends introduced in the scenarios are in accordance to the Sobol's sequence for the establishment of a representative sampling of values' sequences.

Crop	Initial sow day	Assumed change by 2045 (days)	Final sow day
W. Barley	259	7	266
W. Wheat	270	7	277
W. Rapeseed	239	7	246
S. Barley	84	-7	77
S. Maize	118	-7	111

Table 3.1: *Assumed change in sowing days by 2045 for scenarios 3-6*

Crop	Initial harvest day	Assumed change by 2045 (days)	Final harvest day
W. Barley	210	-12	198
W. Wheat	235	-12	223
W. Rapeseed	225	-12	213
S. Barley	223	-12	211
S. Maize	275	-12	263

Table 3.2: *Assumed change in harvesting days by 2045 for scenarios 3-6*

Scenario 3: Fieldwork effect with short gap (FW effect - Short gap)

Discourse: In this scenario, it is assumed that future climate change trends will result in adverse yield developments for most of the crops. Furthermore, the scenario is designed so that the trends of (ideal) dates in which several fieldwork operations should be performed (ideal dates with respect to their phenological developments) vary as a result of climate change. Also, this scenario controls the extent to which winter rapeseed can be grown after winter wheat. In this scenario, no initial machinery endowment is provided to the farm agent. Effects:

1. The yields of winter wheat, winter barley, spring barley, and winter rapeseed show an uncertain, mostly negative trend. The yields of these crops show trends that range between 2 and -14 percent by 2045 . These variations are established following the sampling proceadure of the Sobol's sequence. Silage maize is assumed to profit from warmer conditions and this is reflected in a positive uncertain trend in yields. Yields for this crop show an increase by 2045 in the range between 0 and 15 percent. Selling maize can be done up to an uncertain level in the range of 900-1,600 (t).

2. The trend of shift of the ideal sowing and harvesting days is assumed to move in time as shown in tables 3.1 and 3.2 respectively.

3. The minimum day-gap between the sowing of winter rapeseed and harvesting winter wheat is considered "short" and uncertain. A minimum day-gap trend that moves between 0 and 2 days does allow growing rapeseed after winter wheat at early simulation periods.

4. The trends of ideal fertilization dates are considered uncertain. The shifts of the dates of dynamic fertilization operations are subject to uncertainty. These trends move in a range of -12 and -6 days by 2045.

Scenario 4: Fieldwork effect with long gap (FW effect - Long gap)

Discourse: In this scenario, most of the experimental set-up from Scenario 3 (FW effect - Short gap) is replicated, yet it differs in one aspect. The difference in this fourth scenario is that the minimum day-gap between the sowing of winter rapeseed and harvest of winter wheat is considered “long” and uncertain. A minimum day-gap between 5 and 8 days is here assumed.

Scenario 5: Fieldwork effect with short gap and higher maize production allowance (FW effect - S. Maize - Short gap)

Discourse: In this scenario, most of the experimental set-up from Scenario 3 (FW effect - Short gap) is replicated, yet it differs in one aspect. The difference in this fifth scenario is that the maximum limit of silage maize sells is relaxed and the agent is able to sell a higher level of yield at the market. The new upper limit for maize yield is subject of uncertainty and ranges between 3,000 - 2,500 (t).

Scenario 6: Fieldwork effect with long gap and higher maize production allowance (FW effect - S. Maize - Long gap)

Discourse: In this scenario, most of the experimental set-up from Scenario 3 (FW effect - Short gap) is replicated, yet it differs in two aspects. The first difference in this scenario is that the maximum limit of silage maize sells is relaxed and the agent is able to sell a higher level of yield at the market. The new upper limit for maize yield is subject of uncertainty and ranges between 3,000 and 2500 (t). The second difference in this scenario is that the minimum day gap between the sowing of winter rapeseed and winter wheat is considered “long” and uncertain. A minimum day-gap between 5 and 8 days is here assumed. The table 3.3 shows a summary of all scenarios. Additional uncertain parameters considered are presented in the documentation section (Chapter six).

Baseline scenario

Considers simulations with the model with all the base uncertain input parameters described in the documentation section. No yield trends or trends in timing of field operations are considered in the baseline scenario. Winter rapeseed is not possible after winter wheat. Selling maize can be done up to an uncertain level in the range of 900-1,600 (t). In this scenario, no initial machinery endowment is provided to the farm agent.

Overview of scenarios

Dimension	Scenario 1: Positive yield effect	Scenario 2: Negative yield effect	Scenario 3: Fieldwork effect Short gap (FW- effect- Short gap)	Scenario 4: Fieldwork effect Long gap (FW-effect- Long gap	Scenario 5: Fieldwork effect Higher maize production Short gap (FW- effect- S.Maize- Short gap)	Scenario 6: Fieldwork effect Higher maize production Long gap (FW- effect- S.Maize- Long gap)
Crops with certain yield trend (% by 2045)	WH (+15%)	WH WB SB (-14%)	-	-	-	-
Crops with uncertain yield trend (% by 2045)	WB SB WR (range: 0,+ 15%) SM (range: 0,+15%)	SM (range: 0,+15%) WR (range: -14%, 0)	WH WB SB WR (range: -14%, +2%) SM (range: 0,+15%)	WH WB SB WR (range: -14%, +2%) SM (range: 0,+15%)	WH WB SB WR (range: -14%, +2%) SM (range: 0,+15%)	WH WB SB WR (range: -14%, +2%) SM (range: 0,+15%)
Min. day-gap harvest w. wheat sowing w. rapeseed	6 days	6 days	Uncertain range: 0 - 2 days	Uncertain range: 5-8 days	Uncertain range: 0 - 2 days	Uncertain range: 5-8 days
Change of sowing date by 2045	Constant	Constant	As depicted in table 3.1	As depicted in table 3.1	As depicted in table 3.1	As depicted in table 3.1
Change of harvest date by 2045	Constant	Constant	As depicted in table 3.2	As depicted in table 3.2	As depicted in table 3.2	As depicted in table 3.2
Uncertain fertilization dates	Constant	Constant	Range: -12 and -6 days by 2045	Range: -12 and -6 days by 2045	Range: -12 and -6 days by 2045	Range: -12 and -6 days by 2045
S. maize uncertain sells upper limit	900-1,600 (t)	900-1,600 (t)	900-1,600 (t)	900-1,600 (t)	2,500-3,000 (t)	2,500-3,000 (t)

Table 3.3: *Overview of scenario definition for experimental design. No baseline scenario shown.*

3.1.4 Results

Effects on land-use

Figure 3.1 shows the simulation results for land-use over 25 simulation periods and 50 uncertainty design points of the Sobol's sequence for the baseline scenario. The figure shows that land use's highest share corresponds to winter wheat (approx. a median value 43-45 percent of the arable land). Winter barley, winter rapeseed, and fallow are additional significant land uses for the 150-hectare farm agent. Silage maize and spring barley represent the smallest shares of land-use. The effects of "*Scenario 1: Positive yield effects*" and "*Scenario 2: Negative yield effects*" simulations on land-use decisions are presented in the annexes of this thesis (Figure 6.8). In general, the results of these two "yield scenarios" show land-use results that are very similar to the ones presented for the baseline scenario. Land-uses for "*Scenario 1: Positive yield effects*" and "*Scenario 2: Negative yield effects*" are relatively stable. Slight differences with the baseline scenario arise only for the interquartile ranges of the box-plots of winter wheat; these ranges are downward biased in the scenario where yields for winter wheat experience a negative trend over the simulated years, yet, the general median wheat area remains stable like the one observed in the baseline scenario in Figure 3.1.

Interesting results derive from the scenarios that introduce trends in the ideal times of fieldwork operations. Land-use results are presented for "*Scenario 3: FW effect - Short gap*" and "*Scenario 4: FW effect - Long gap*" in Figure 3.2, and "*Scenario 5: FW effect - S. Maize - Short gap* " and "*Scenario 6: FW effect - S. Maize - Long gap* " in Figure 3.3. The description of the results concentrates on the significant observed trends and are further discussed in the next subsection:

(1) Substitution effect between spring barley and winter barley. In the scenarios "*Scenario 3: FW effect - Short gap*" and "*Scenario 4: FW effect - Long gap*" (Figure 3.2) it is possible to observe that in simulation periods 9-10, the simulated spring barley area starts to increase. There is an important expansion in the land-use share of spring barley's area until simulation period 15, and from this point in time onwards, this share of the area remains stable until the end of the simulation periods. Moreover, between the simulation periods 9 to 15, the simulated winter barley area experiences decreases in both of the presented scenarios. This decrease lasts until simulation period 16, where the winter barley area increases for a brief time only to fall once again for the simulation periods 20 and beyond.

(2) Wheat area and fallow area. Land-use results for the scenarios "*Scenario 3: FW effect - Short gap*" and "*Scenario 4: FW effect - Long gap*" (Figure 3.2) reveal that winter wheat's median area experiences a significant decrease from the simulation periods 16 and beyond. This development seems to be correlated with two land-use changes occurring at the same time: i) An increase in the fallow area, and ii) a sudden significant increase of the median area and variance of winter barley from the simulation period 16 to simulation periods 18-19.

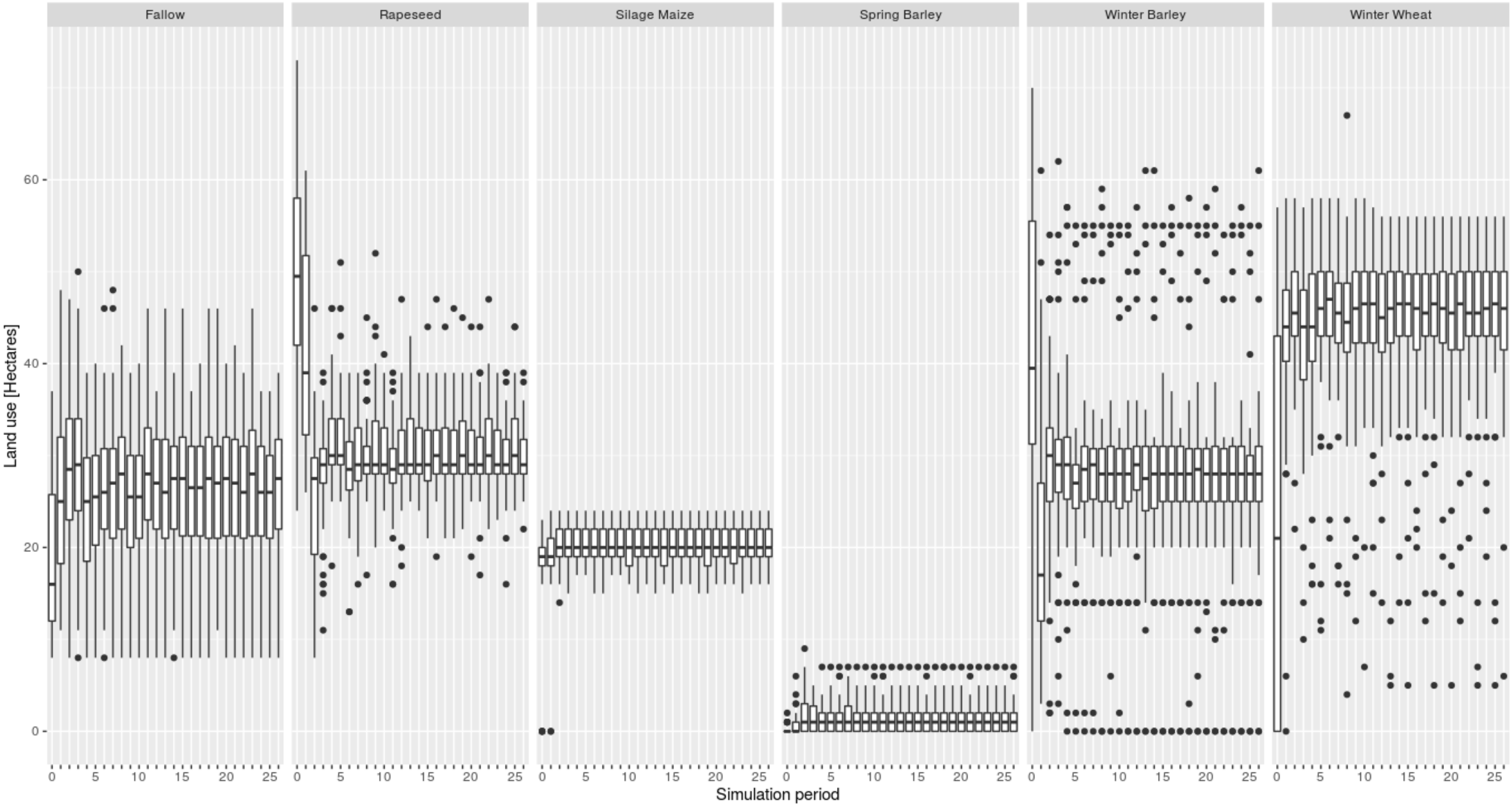

Figure 3.1: *Simulated land use over 25 years. Baseline scenario. Results over 50 design points of the Sobol's sequence*

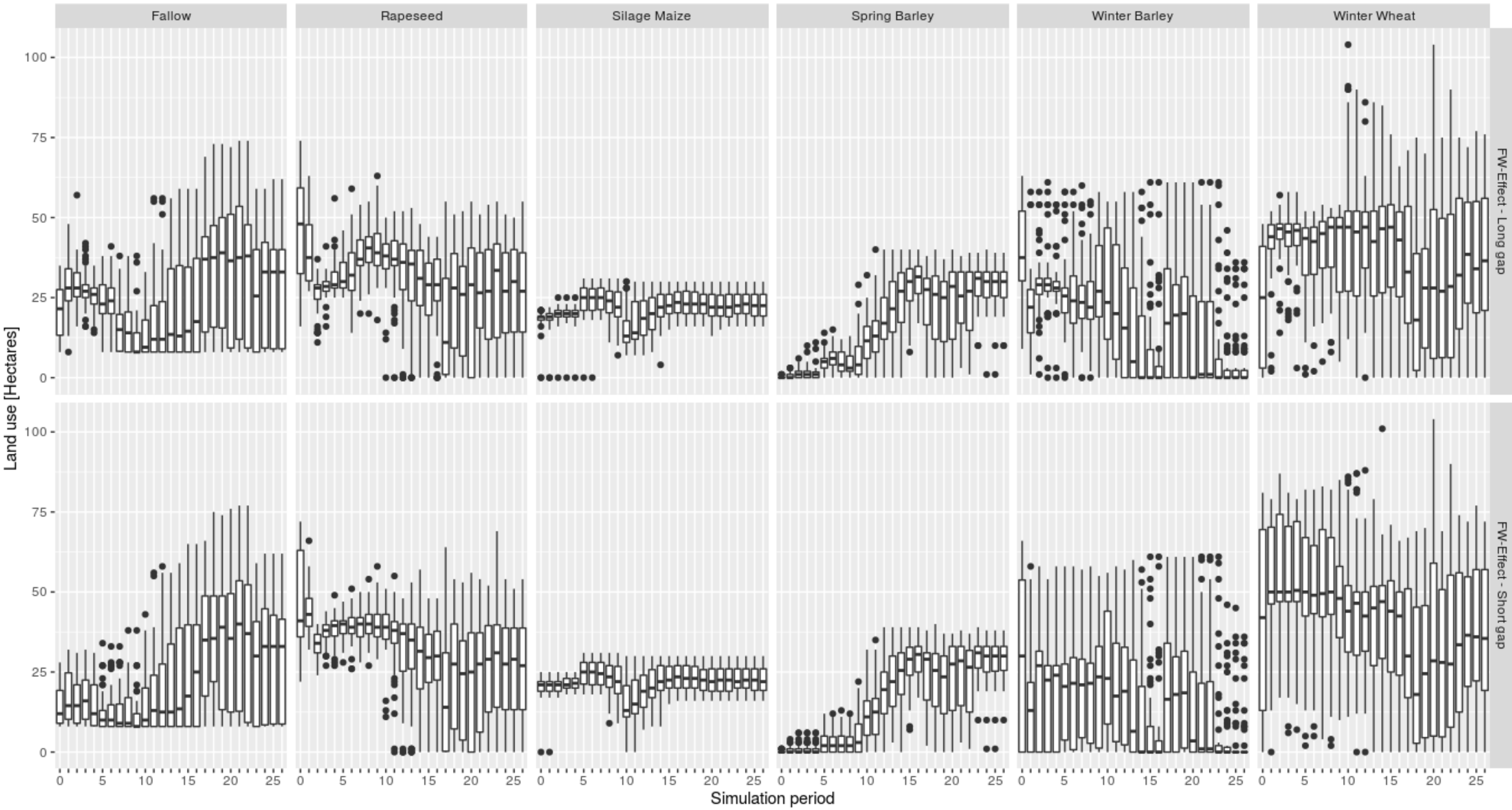

Figure 3.2: *Simulated land use over 25 years. "Scenario 3: Fieldwork effect with a short gap (FW effect - Short gap)" and "Scenario 4: Fieldwork effect with a long gap (FW effect - Long gap)". Results over 50 design points of the Sobol's sequence*

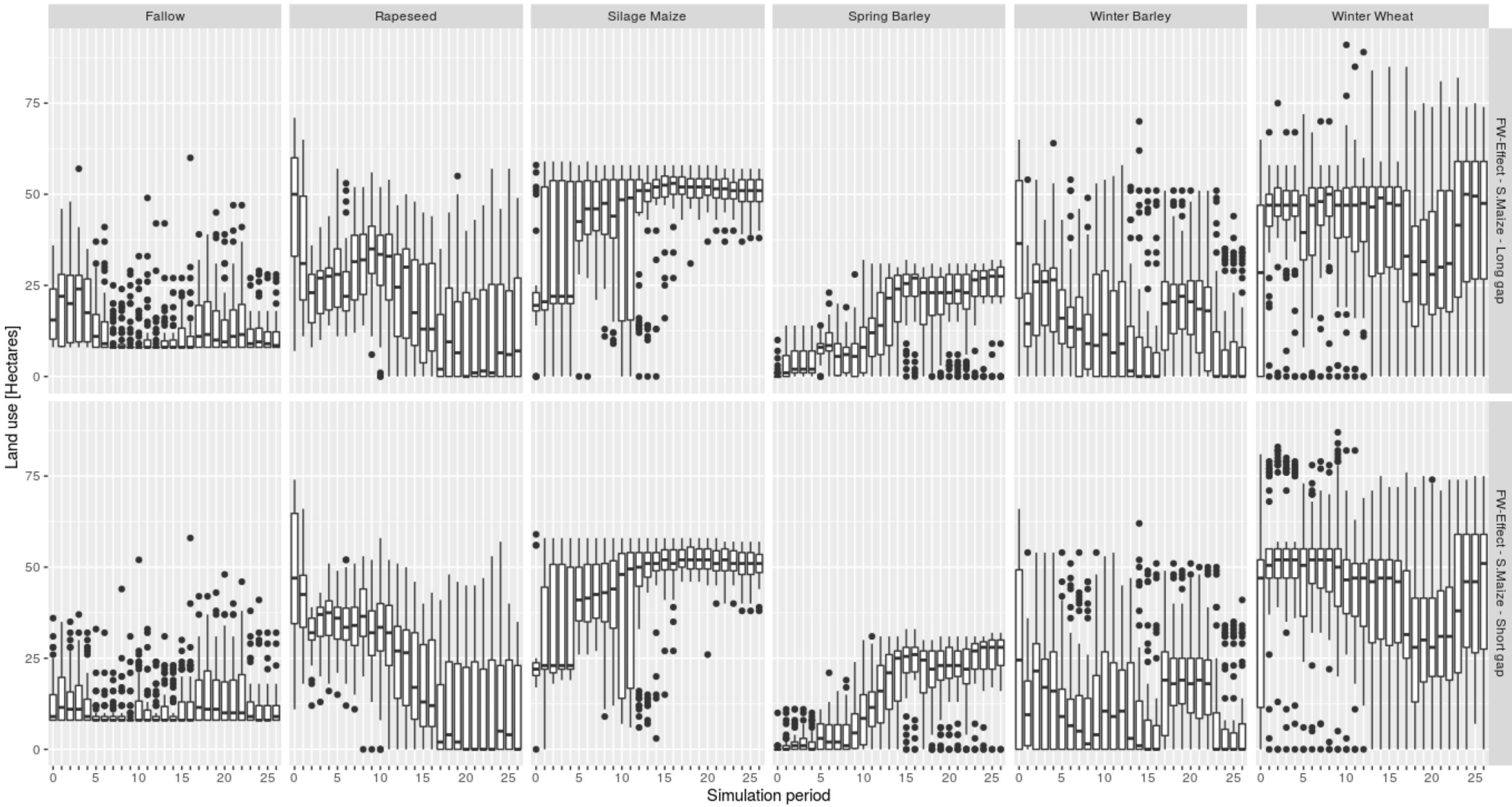

Figure 3.3: *Simulated land use over 25 years. "Scenario 5 : Fieldwork effect with short gap and higher maize production allowance (FW effect - S. Maize - Short gap)" and "Scenario 6 : Fieldwork effect with long gap and higher maize production allowance (FW effect - S. Maize - Long gap)". Results over 50 design points of the Sobol's sequence*

(3) Silage maize area increases from simulation period four to five and remains at a high level. Figure 3.3 shows the land-use results of the simulations of the scenarios where the farm agent is able to sell maize at a higher upper sales limit. The land-use results for the simulations "*Scenario 5: FW effect - S. Maize - Short gap*" and "*Scenario 6: FW effect - S. Maize - Long gap*" show that the area of silage maize experiences a high variance over the uncertainty points of the Sobol's sequence at early simulation periods (i.e., 0-4) , this is represented by the interquartile range of the boxplots. Moreover, from the simulation period 4 to 5, the median area of silage maize increases significantly and remains stable from that point in time and onwards.

(4) The production of winter barley is retaken. Figure 3.3 shows that the simulated farm agent retakes winter barley production in the simulation period 17 but it stops this production a simulation period 23. This land-use course can be observed for the scenarios "*Scenario 5: FW effect - S. Maize - Short gap*" and "*Scenario 6: FW effect - S. Maize - Long gap*". In the figure 3.2 the production of winter barley is also retaken in the simulation period 17, and also this production is mostly stopped from simulation period 23 onwards.

(5) Crop rotation. Winter rapeseed after winter barley. The crop rotation effect of a short or a long minimum day-gap between the ideal harvesting date of winter wheat and the ideal sowing date of winter rapeseed on winter rapeseed area can be observed in the figures 3.4 and 3.5. The simulated farm agent is able to produce winter rapeseed after winter wheat consistently at simulation period seven when the minimum day-gap ranges between 5 and 8 days. The scenario that faces a minimum day-gap in the range of 0 and 2 days allows the farm agent to produce winter rapeseed after winter wheat at early simulation periods.

Effects on machinery investment and replacement costs

Figures 3.6, 3.7, and 3.8 show the investment and replacement costs on machinery and equipment for each simulation period across several scenarios (Thsd. Euros). The left-side of the illustrations shows the distribution of the investments in the technologies across the 50 design points of the Sobol's sequence on box-plots. For a better appreciation, the right-side illustration shows the same 50 design points with a line that represents the median value of the distribution.

The results from the three figures reveal that there are regular phases in which machinery replacements take place. At the beginning of the simulations, the simulated agent acquires equipment that results in overall investment values between 100 and 200 thousand euros. The high investment value in the second simulation period results from the acquisition of harvesting equipment (the model is designed so that the harvesting operations take place in $t+1$. See documentation of model structure in chapter six).

3.1.5 Discussion

The discussion of land-use and machinery acquisition outcomes is organized in correspondance to the descriptions of the significant trends identified in the subsection "3.1.4 Results". Further discussion elements are provided in regard to the adequacy of the experimental design and relevant factors to consider when analyzing the sensitivity of the

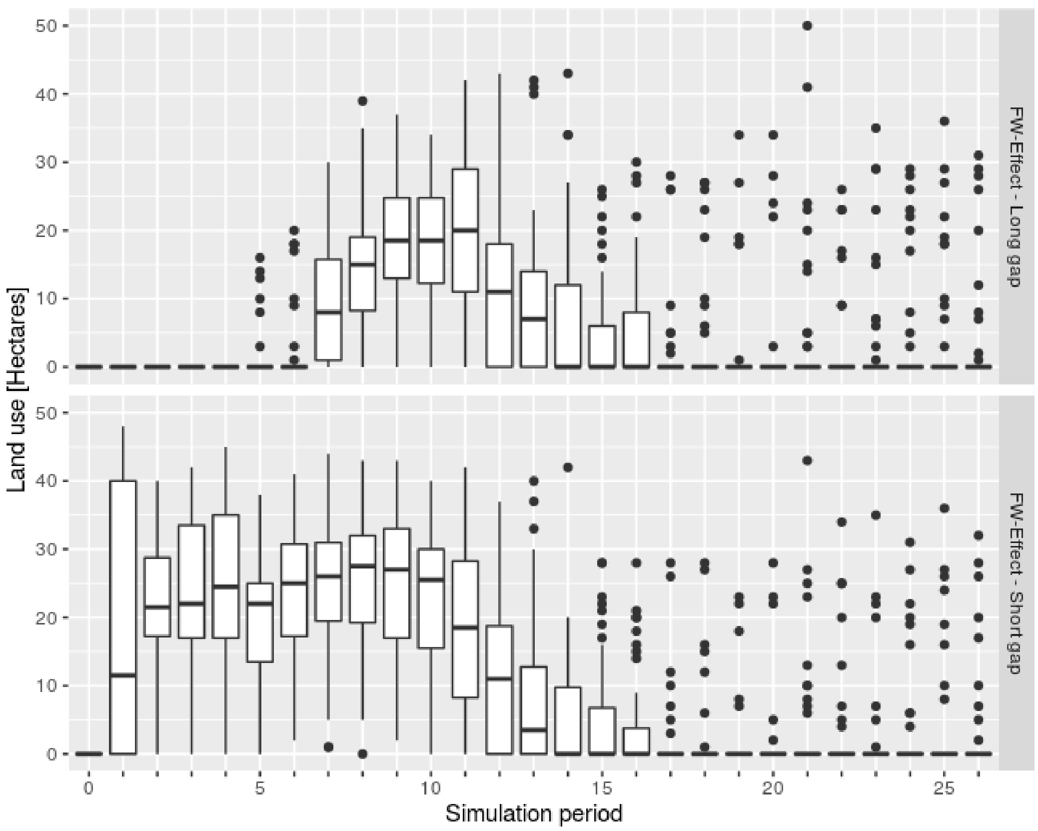

Figure 3.4: *Scenarios "FW effect - Long gap" and "FW effect - Short gap". Rapeseed area after winter wheat. Results over 50 design points of the Sobol's sequence*

MPMAS model results.

(1) Substitution effect between spring barley and winter barley: The change in the land-use reflected in an increase of spring barley's area and a decrease of winter barley's area (Figure 3.2) is the response to a complex interaction between many crops and their associated fieldwork demands. In the simulation period in which the spring barley area begins to increase, the simulated farm agent experiences, that for some crops, the ideal date for a fertilization operation shifts from the second half of March towards the first half of the month.

The ideal dates of fertilization of winter rapeseed, winter wheat, and winter barley shift towards the first half of March, whereas spring barley's ideal fertilization timing still remains in the second half of March. In general, this first half of March depicts a tighter time window for performing field operations than the second half (1.83 days less on average across weather levels and soil resistances). Before the ideal fertilization date shifted towards the first half of March for the mentioned crops, there was low production of spring barley; this is because winter rapeseed, winter wheat, and winter barley dominated the land use and this predominance of land-use among these three crops means that spring barley needed to compete for work time to perform fertilization tasks.

After the shift of the optimal fertilization dates for winter rapeseed, winter wheat, and winter barley towards the first half of March, the new time competition to conduct the necessary fertilization tasks among these crops drives the farm agent to optimally adjust its land-use pattern and engage in a step-wise reduction of the area of winter rapeseed and

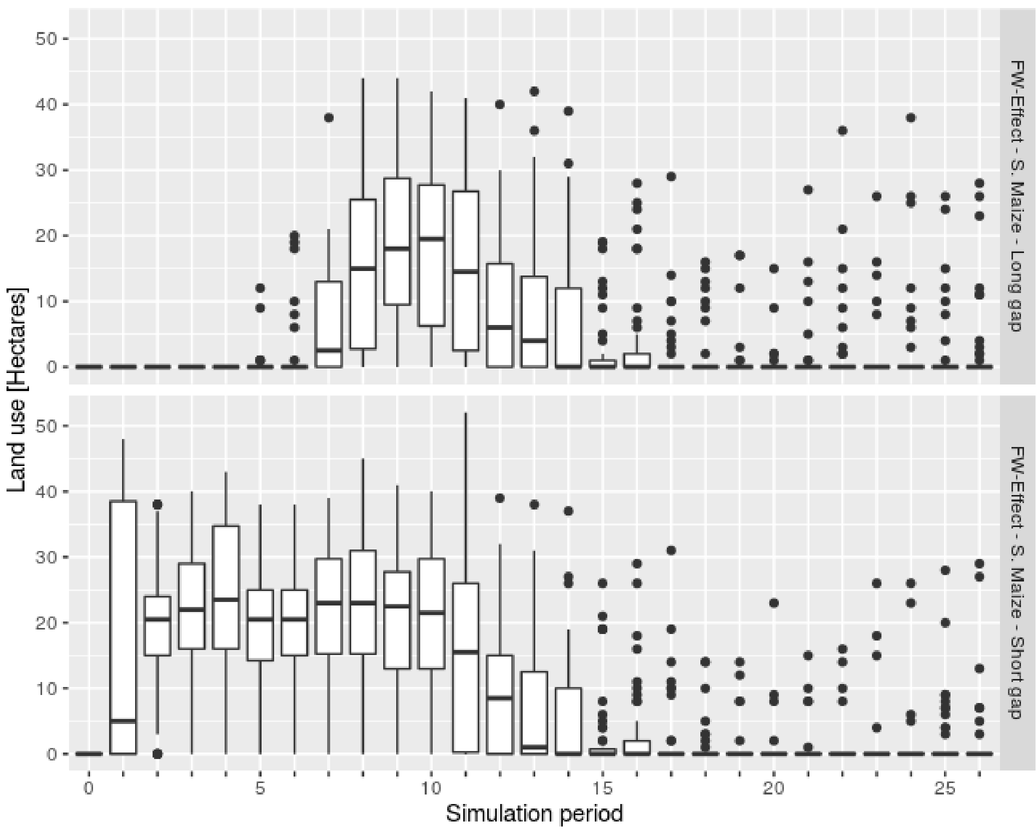

Figure 3.5: *Scenarios "FW effect - S. Maize - Long gap" and "FW effect - S. Maize - Short gap". Rapeseed area after winter wheat. Results over 50 design points of the Sobol's sequence*

winter barley, and a maintenance of the area of winter wheat for the coming simulation periods (until the next relevant land-use change takes place). With the shifts of the ideal fertilization dates, a crowding-out effect occurs: The spring barley area substitutes the winter barley area due to the less competition that spring barley faces for fieldwork time in the second half of the month.

Table 3.4 shows an example of the effective and planned replacements in machinery that the simulated farm agent foresees in the simulation period that corresponds to one year before experiencing a shift in the ideal dates of fertilization fieldwork for the crops discussed. Furthermore, table 3.5 shows the effective and planned machinery portfolio in the simulation year where the agent experiences the fieldwork shift and adapts its land-use (as described above). These machinery replacement examples shown in tables 3.4 and 3.5 are derived from a detailed examination of an agent-decision matrix of a Sobol's design point that was selected, tested and subject of sensitivity stress (similar replacement portfolios courses were observed when alternative design points of the scenarios "*Scenario 3: FW effect - Short gap*" and "*Scenario 4: FW effect - Long gap*" were investigated).

The comparison of the replacement portfolios depicted in tables 3.4 and 3.5 indicates that the farm agent is able to achieve most of its machinery replacement plan by adapting its land-use decisions. This observation is supported by stress –and hypothetical– simulation runs that were performed for individual decision matrices of several design points of the discussed scenarios. The stress runs can be understood as *"failing to adapt"* or

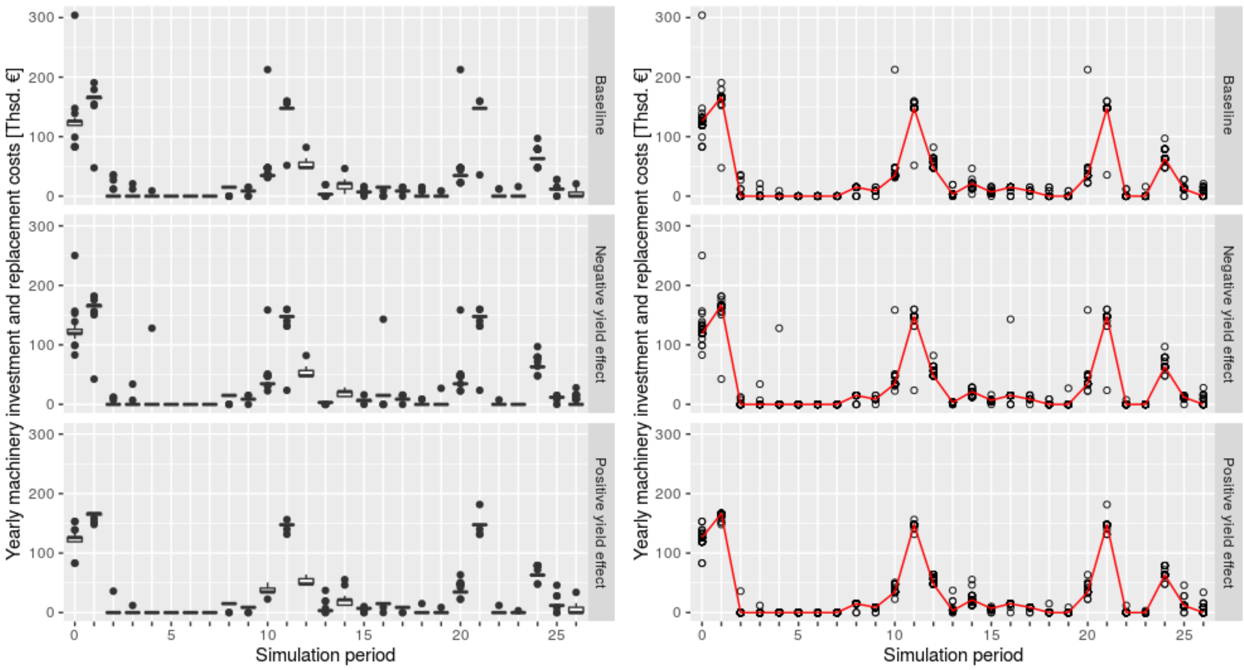

Figure 3.6: *Yearly machinery and replacement investment costs scenarios "Baseline scenario", "Positive yield effects" and "Negative yield effects". Results over 50 design points of the Sobol's sequence.*

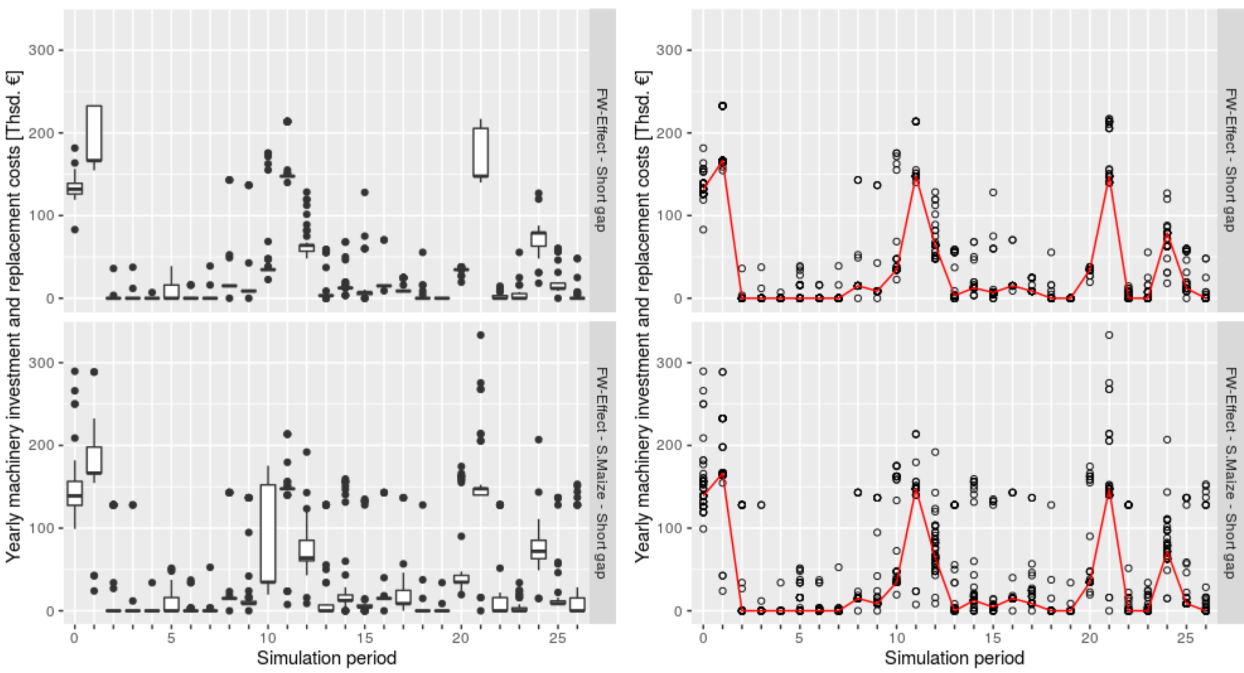

Figure 3.7: *Yearly machinery and replacement investment costs scenarios "FW effect - Short gap" and "FW effect - S. Maize - Short gap". Results over 50 design points of the Sobol's sequence.*

"sticking to my plan no matter what" situations. The stress runs revealed that, whenever the farm agent is hypothetically restricted to comply with the land-use pattern that was previously planned when a shift in the ideal fertilization date was not yet foreseen, then

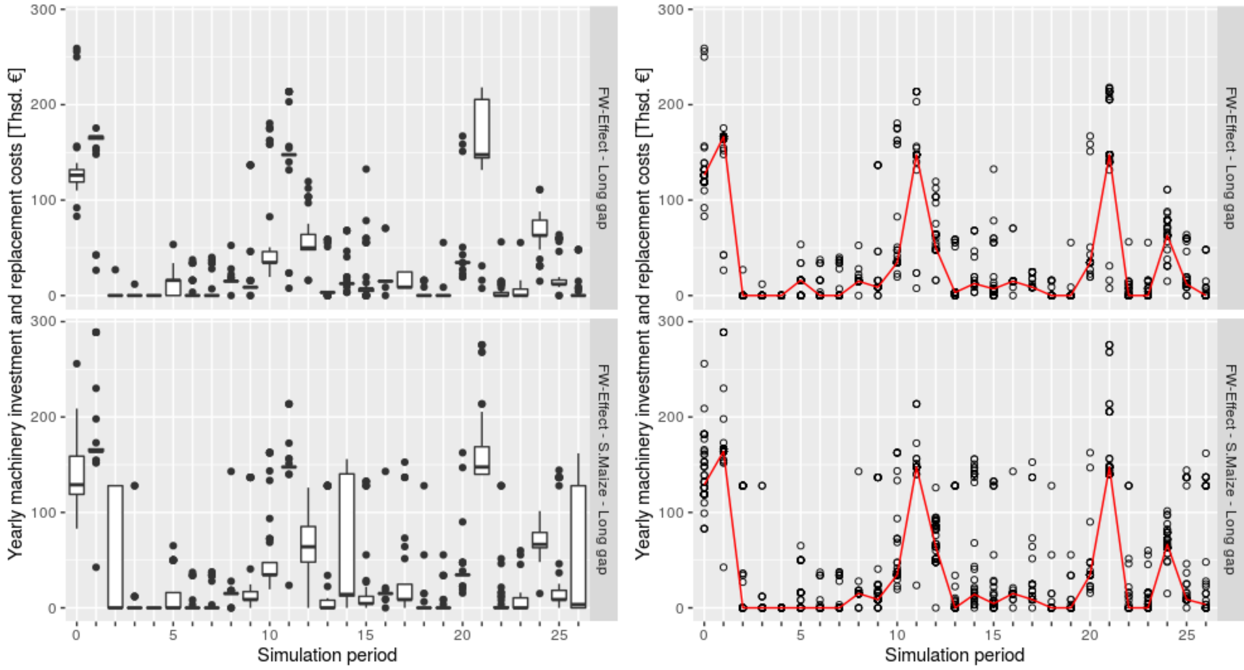

Figure 3.8: *Yearly machinery and replacement investment costs scenarios "FW effect - Long gap" and "FW effect - S. Maize - Long gap". Results over 50 design points of the Sobol's sequence.*

it would be forced to significantly adjust its machinery replacement plan, while resulting in a less profitable situation (lower objective function value) than by adequately adapting the land-use.

Results from stress and hypothetical runs indicated that failing to adapt the land-use in light of a shift in the ideal dates of fertilization in March would require an additional investment in a tractor (67 kW) and an additional centrifugal spreader of 1,500 liters. Moreover, the demand for labor (with a quarter of a full position per year) would increase from 3 units to 9-10 units across the evaluated design points of the Sobol's sequence. A lower discounted sum of cash withdrawals was additionally observed (discounted sum of cash withdrawals over the planning horizon) if the farm agent is restricted to not adapt its land-use pattern in light of a shift in the fertilization dates of the crops under consideration. It is relevant to remark that this "fertilization effect" here described does not occur at exactly the same simulation periods (i.e., always from simulation period 9 towards 10). The shifts in the ideal fertilization dates for the crops here considered enter the simulations as uncertain factors by employing the Sobol's sequence, and these move in the range of 12 and 6 days. This is why there is no sudden increase of the spring barley area from one simulation period to another, but rather a slowly increasing trend between simulation periods 10 and 15.

(2) Wheat area and fallow area: For the analysis and interpretation of the simulated courses of winter wheat and fallow in "*Scenario 3: FW effect - Short gap*" and "*Scenario 4: FW effect - Long gap*", it becomes relevant, at this point, to simultaneously discuss the winter wheat and fallow area courses resulting from "*Scenario 5: FW effect - S. Maize - Short gap*" and "*Scenario 6: FW effect - S. Maize - Long gap*". Are the dynamics of winter wheat and fallow areas really closely interrelated? In order to understand the interplay between winter wheat trends and fallow a few observations on the

Planning period	Equipment units	Equipment type
1	1 (each)	Tractor 4x4-45 kW, Heavy cultivator (Schwergrubber angebaut), 2 m Rotary harrow (Kreiselegge angebaut), 3 m Centrifugal spread (Schleuderstreuer angebaut), 800 l
2	1	Wing share cultivator (Flügelschargrubber angebaut), 3 m
3	1	Precision seeder maize, 4 rows (Einzelkornsämaschine -Mais, 4 reihig)
4	1	Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)
7	1 (each)	Centrifugal spread (Schleuderstreuer angebaut), 1500 l Plant protection sprayer tank with pump attached 1000 l Spray boom 15 m (Spritzgestänge 15 m)
8	1 (each)	Combine harvester 125 kW, Grain header 4.5 m Rapeseed attachment 4.5 m

Table 3.4: *Machinery replacements planned one simulation period before the simulated farm agent experiences a shift in the fertilization dates of the concerned crops.*

Planning period	Equipment units	Equipment type
1	1	Wing share cultivator (Flügelschargrubber angebaut), 2 m
2	1	Precision seeder maize, 4 rows (Einzelkornsämaschine -Mais, 4 reihig)
3	1	Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)
6	1 (each)	Centrifugal spread (Schleuderstreuer angebaut), 1500 l Plant protection sprayer tank with pump attached 1000 l Spray boom 15 m (Spritzgestänge 15 m)
7	1 (each)	Combine harvester 125 kW, Grain header 4.5 m Rapeseed attachment 4.5 m
10	1 (each)	Tractor 67 kW Centrifugal spread (Schleuderstreuer angebaut), 800 l Pneumatically mounted seed drill, 3m (Sämaschine pneumatisch angebaut 3m) Precision seeder maize, 4 rows (Einzelkornsämaschine -Mais, 4 reihig)

Table 3.5: *Machinery replacements performed and planned at simulation period where the simulated farm agent experiences a shift in the fertilization dates of the concerned crops and it is able to adapt its land-use plan.*

courses of the land-use patterns of other crops are first required.

First: Figure 3.3 shows the land-use courses for the scenarios where maize sales have a new and higher upper limit; this allows the farm agent to produce more maize and use more area for silage maize. The figure shows that the median area of silage maize increases in the first simulation periods and remains stable at around 50 hectares in the following periods. Also, the median area of fallow observed in figure 3.3 is much lower than the one observed in the "*Scenario 3: FW effect - Short gap*" and "*Scenario 4: FW effect - Long gap*" in figure 3.2 [2].

Second: It is also important to notice that the land-use courses of winter wheat, spring barley, and winter barley are very similar between the figures 3.2 and 3.3. Given that the land-use trends of these crops in the corresponding scenarios represented in figures 3.2 and 3.3 show similar courses, it is reasonable to assert that the high share of fallow land that is observed in figure 3.2 from simulation period 16 onwards results rather from an interplay between of production decisions of winter rapeseed, silage maize and fallow and not due to a direct relationship with the area of winter wheat.

Third: At the beginning of the simulations of the "*Scenario 3: FW effect - Short gap*" and "*Scenario 4: FW effect - Long gap*" (Figure 3.2), the production of rapeseed is strongly dependent on the previously grown areas of winter barley and winter wheat (if the minimum day-gap between harvest of wheat and seeding of winter rapeseed allows it). This can be confirmed by observing figure 3.9. The figure shows the area of winter rapeseed that is grown after each of the distinguished land-uses (rapeseed after fallow, spring barley, winter barley, or winter wheat). The figure corresponds to "*Scenario 4: FW effect - Long gap*" (the "*Scenario 3: FW effect - Short gap*" is shown in figure 3.10).

Fourth. The "fertilization effect" discussed in the previous paragraphs –"(1) Substitution effect between spring barley and winter barley"– reduces the scope of production of winter rapeseed after winter barley (due to the crowding-out effect resulting in a decrease of the winter barley area). This situation drives the farm agent to redefine its land-use pattern in a way that the fallow area is sufficiently provided for the future production of winter rapeseed. Moreover, in the scenarios where silage maize has a higher allowance for sales, the agent does not show a consistent increase of the fallow area for the purposes of future production of winter rapeseed after the fertilization effect between simulation periods 10-15 [3]. This dynamic results in a significant decrease in the production possibilities of winter rapeseed.

The examinations described above by comparing figures 3.2 and 3.3 do not really explain why there is a sudden decrease in the area of winter wheat from simulation period 16 onwards in figure 3.2, but they so far suggest that the increases in fallow area and the decreases of winter wheat area are less correlated than one might think at first glance [4]. The decrease in winter wheat area is associated, instead, with the course of the area of winter barley.

[2]The farm agent is required to have a minimum of fallow area in this model version due to abstractions in the implementation of EU policy requirements. See documentation in chapter 6.

[3]The winter rapeseed area after the previous land-uses for the "Scenario 6: FW effect - S. Maize - Long gap" is shown in the section "3.3 Validation", in the figure 3.27

[4]Ultimately, there is, of course, a correlation in the sense that one additional hectare of one crop means one hectare less of another crop due to the fixed arable land of the farm agent, the reference is made here in terms of correlation of decisions for substituting one crop for another as an optimal decision.

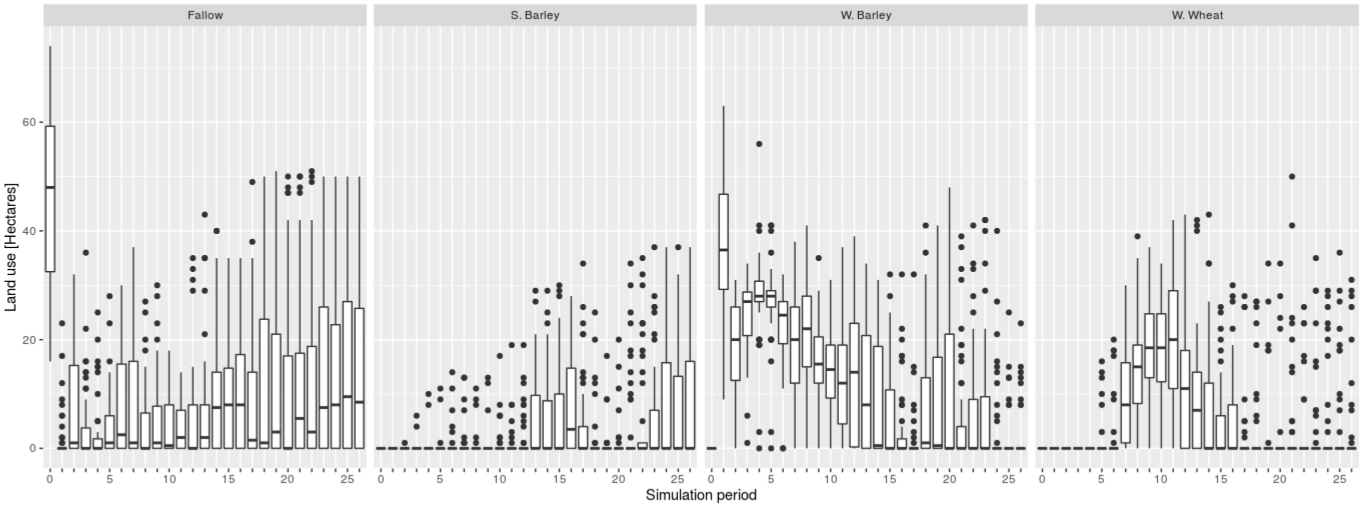

Figure 3.9: *Area of winter rapeseed grown after fallow, spring barley, winter barley and winter wheat. Results for scenario "FW effect - Long gap" for 50 design points of Sobol's sequence.*

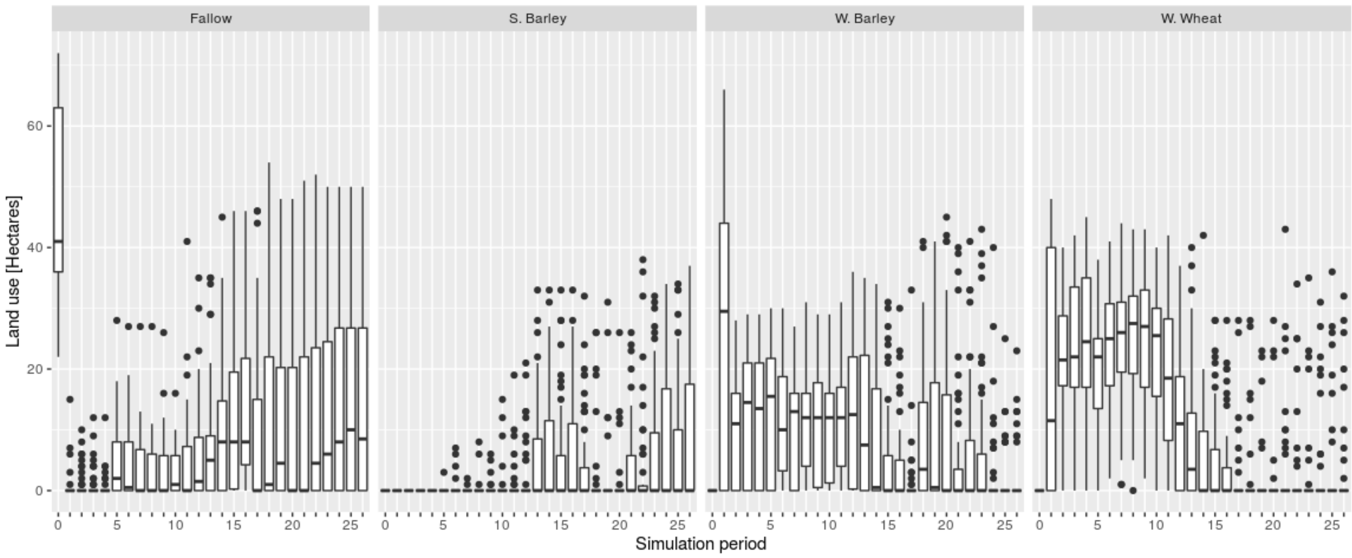

Figure 3.10: *Area of winter rapeseed grown after fallow, spring barley, winter barley and winter wheat. Results for scenario "FW effect - Short gap" for 50 design points of Sobol's sequence.*

The reason why it is possible to observe a decrease in the winter wheat area starting at the simulation period 16 in the figure 3.2 is that the ideal harvesting day of this crop shifts from the second half towards the first half of August in simulation period 17. This shift in winter wheat harvesting's ideal date means that this crop's harvesting operations enter now in (time) competition with winter rapeseed and spring barley harvesting operations. In contrast, winter barley's ideal harvesting timing occurs in the second half of July and does not pose competition for harvesting operations with these other crops. This shift in the ideal harvesting date of winter wheat triggers a land-use adaptation. The winter wheat and winter rapeseed median areas are decreased, and the area of spring barley remains relatively stable. This adaptation results in a total decrease of the area

Planning period	Equipment units	Equipment type
1	1	Precision seeder maize, 4 rows (Einzelkornsämaschine -Mais, 4 reihig)
2	1	Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)
5	1 (each)	Centrifugal spread (Schleuderstreuer angebaut), 1000 l Vacuum tanker 7 m3 Spray boom 15 m (Spritzgestänge 15 m)
6	1 (each)	Combine harvester 125 kW, Grain header 4.5 m Rapeseed attachment 4.5 m
9	1 (each)	Tractor 67 kW Centrifugal spread (Schleuderstreuer angebaut), 1000 l Pneumatically mounted seed drill, 3m (Sämaschine pneumatisch angebaut 3m) Precision seeder maize, 4 rows (Einzelkornsämaschine -Mais, 4 reihig)
10	1	Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)

Table 3.6: *Machinery replacements planned one simulation period before the simulated farm agent experiences a shift in the ideal harvesting date of winter wheat.*

dedicated to the three crops: Winter wheat, winter rapeseed, and spring barley. From detailed examinations of specific design points of the Sobol's sequence, it was possible to verify that the overall area dedicated to these three crops decreased from about 85 hectares to approx. 63 hectares depending on the specific Sobol's design point evaluated. Consequently, the land-use adaptation allows winter barley production in the simulation period 17, given the reduction serviced for winter wheat and winter rapeseed areas.

A detailed analysis of agent decision matrices of various design points of the Sobol's sequence was conducted to assess hypothetical stress runs: The agent decision module was hypothetically controlled in a way that the farm agent fails to adapt its land-use decisions at the moment in which it experiences a shift in the ideal harvesting date of winter wheat, and, instead, it complies with the land-use pattern that was planned before experiencing the shift in the harvesting date (this is, strong demand for winter wheat, winter rapeseed, and spring barley area). The controlled and hypothetical exercise complies with the expectation: If this stress situation is implemented in the agent decision module, the farm agent would need to realize a significant –less profitable– adjustment in its machinery and equipment replacement plan.

Table 3.6 shows the effective and planned machinery replacements in the simulation period where the farm agent has not yet experienced a shift in the winter wheat's ideal harvesting date (one simulation period before the shift occurs). Table 3.7 shows the effective and planned replacements for machinery once the simulated farm agent experiences the shift in the harvesting date of winter wheat and it can adapt its land-use decisions. The farm agent keeps its plan for machinery replacements relatively untouched once it is able to adapt its land-use decisions.

Table 3.8 shows the effective and planned machinery replacements in the simulation period where the farm agent experiences a shift in winter wheat's ideal harvesting date, but the agent decision module is stressed and hypothetically restricted to comply with its previously established land-use plan one year before the shift in the harvesting date is experienced. Under the new stressed and restricted conditions for evaluation, the farm agent would need to adapt its optimal machinery replacement plan and acquire an additional tractor and a combine harvester to deal with the harvesting demands. This would also require that the agent increases its demand for hired labor from 2 to 4 units (workers with a quarter of a full position per year).

Planning period	Equipment units	Equipment type
1	1	Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)
4	1 (each)	Centrifugal spread (Schleuderstreuer angebaut), 1000 l Vacuum tanker 7 m3 Spray boom 15 m (Spritzgestänge 15 m)
5	1 (each)	Combine harvester 125 kW, Grain header 4.5 m Rapeseed attachment 4.5 m
8	1 (each)	Tractor 67 kW Pneumatically mounted seed drill, 3m (Sämaschine pneumatisch angebaut 3m) Precision seeder maize, 4 rows (Einzelkornsämaschine -Mais, 4 reihig)
9	1	Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)
10	1 (each)	Tractor 67 kW Centrifugal spread (Schleuderstreuer angebaut), 1500 l

Table 3.7: *Machinery replacements planned at simulation period where the simulated farm agent experiences for the first time a shift in the ideal harvesting date of winter wheat and is free to adapt its land-use plan.*

Planning period	Equipment units	Equipment type
1	1 (each)	Tractor 67 kW Centrifugal spread (Schleuderstreuer angebaut), 1500 l Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)
2	1	Combine harvester 125 kW
4	1 (each)	Centrifugal spread (Schleuderstreuer angebaut), 1500 l Plant protection sprayer tank with pump attached 1000 l Spray boom 15 m (Spritzgestänge 15 m)
5	1 (each)	Grain header 4.5 m Rapeseed attachment 4.5 m
8	1 (each)	Pneumatically mounted seed drill, 3m (Sämaschine pneumatisch angebaut 3m) Precision seeder maize, 4 rows (Einzelkornsämaschine -Mais, 4 reihig)
9	1	Special maize chopper, 1 row (Spezial Maishäcksler, angebaut, 1 reihig)
10	1	Tractor 67 kW

Table 3.8: *Machinery replacements planned at simulation period where the simulated farm agent experiences for the first time a shift in the ideal harvesting date of winter wheat and the model is controlled to comply with the land-used plan expected one year before, where no harvesting date of winter wheat was expected.)*

(3) Silage maize area increases from simulation period four to five and remains at a high level: The reason for the sudden increase in the median area of maize in figure 3.3 is a shift in the ideal dates of harvesting and silaging fieldwork operations of silage maize produced without intermediate crop. From the simulation period 4 towards period 5, both fieldwork operations' ideal dates move from the first half of October to the second half of September. In the second half of September, there are other fieldwork activities that need to be performed, namely, the sowing operations for winter barley and winter wheat, as well as pesticide and fertilizer applications for winter rapeseed. The land-use adaptation consists of an important reduction in the fallow area, and, to a lesser extent, of winter barley area. Detailed examinations of selected design points of the Sobol's sequence revealed that one simulation period before the farm agent experiences a shift in the ideal harvesting and silaging dates of silage maize, its land-use plan for the next year(s) considered keeping the fallow area at a level of approximately 22 to 24 hectares. Once the farm agent experiences the shift in the ideal dates – one simulation period later–, its adaptation consists of a land-use plan where the fallow area is strongly reduced to 9 hectares, which is a reduction that, together with the decrease of area for winter barley production between the simulation periods 5 to 10, allows the farm agent to expand its maize production.

By hypothetically controlling the farm agent's decision module to comply with the land-use pattern established one year before it encountered the shift in the ideal harvesting (and ensilage) date, stress model runs were performed with several Sobol's sequence design points. The stressed runs of the model showed that the farm agent would not need to adapt its optimal machinery replacement plan for this particular effect, but it would require additional labor force for completing the necessary field operations. Not being able to revise the land-use plan would result in a lower objective function value (a lower discounted sum of cash withdrawals) in comparison to a situation where the farm agent can adapt.

(4) The production of winter barley is retaken. In the figure 3.3, it was possible to observe that the farm agent retakes winter barley production in simulation period 17 but it stops this production around simulation period 23. The reason of this land-use change is a shift in the ideal date for spring barley harvesting. The ideal date for harvesting moves from the first half of August in the simulation period 22 towards the second half of July in simulation period 23. This shift means that harvest operations for spring barley enter now in competition with winter barley's harvesting operation in the second half of July. A shift in the harvesting date of spring barley indicates that harvesting operations do not compete anymore with winter wheat harvesting operations, which are still ideally performed in the first half of August. The simulated farm agent adapts in a way that the area of winter barley is reduced, the area of spring barley is slightly increased, and the winter wheat area is strongly increased at the last simulation periods.

The insights presented in this discussion indicated that there is low responsiveness concerning the machinery investment and replacement costs between the different scenarios. The reasons were already hinted in the previous analysis; the simulated farm agent adapts its land-use plan so that the investment plan on the machinery portfolio remains relatively unchanged –changes in machinery investment patterns generally result in less profitable situations than by adapting land-use patterns. Important changes in the optimal machinery portfolio (and labor demand) were instead observed when the farm agent decision module was stressed in hypothetical runs that drove failed adaptation situations in the land-use plan in light of fieldwork timing shifts.

The responsiveness assessment performed for the model component MPMAS of the MPMAS_XN system revealed that the land-use and machinery acquisition outcomes resulting from the scenario simulations are more subtle than one might think. The examination of the different simulation results allowed to discover and disentangle processes' dynamics taking place in the agent decision module in the MPMAS model. The observation of the aggregated trends in land-use and machinery acquisition outcomes needed to be complemented with specific MIP-stress exercises for an improved understanding of causal effects. The MPMAS outcomes' responsiveness is based on complex interactions between farm management decisions and climate change manifestations (trends of shifts in ideal dates for field operations and yield trends over time). The agent-decision module of this model always provides the best feasible outcomes for a given scenario, objective, and constraints, yet, for a better understanding and a good communication of such best-feasible outcomes, it is essential to answer questions like "*What would have happened if the farm agent would not have adapted to the surprises that manifest due to that climate change?*". In the context of the recursive-dynamic simulations here assessed, the inspection of hypothetical stress runs proved useful for answering this question and for transparent communication of the processes that drove the results.

On the approach to examine the model responses. The analysis performed in this subchapter focussed on examining the responses of land-use and machinery acquisition patterns to potential climate change scenarios. The analysis purposefully differs from typical sensitivity analysis (e.g., Elementary Effect or Variance-Based SA) since the objective is not to discover or rank the input parameters that are responsible for a given change in the distribution of an outcome variable; in this current analysis, the input variables are directly controlled (shifts in ideal timing for fieldwork operations and yields), and the interest rests, instead, in exploring their implications with an emphasis on examining the dynamics taking place in the implemented model processes.

On the adequacy of the experimental design. The experimental design consisted of distinctive "scenario-bundles" representing potential climatic manifestations at the farm level. These manifestations were informed by several research results that examine climate change effects on agriculture found in the literature and by opinions of experts familiarized with the research area of the Central Swabian Jura. For some readers, however, the experimental design may seem unusual; the typical scenario-based simulation analysis controls a single variable or model dimension that varies between scenarios. Nevertheless, sensitivity analysis can be performed in a variety of ways (Ragsdale, 2010), and in this subchapter's experimental design, there was a need to balance the portrayal of climate change manifestations (which are complex by definition, and will be complex when running a fully coupled bioeconomic simulation with the MPMAS_XN system) with the number of scenarios to analyze. A focus in one single variable or model dimension at the time (e.g., a change in just one crop's yield trend per scenario) has the potential to strongly increase the number of scenarios that need to be evaluated, this is because interdependencies in the system's variables should be captured and represented in simulating complex human-environment arenas. The approach taken here was to achieve the number of scenarios that enabled an adequate representation of climate change manifestation for the purposes of examining their effects on land-use and machinery investment patterns. The author believes that this has been achieved since the simulation results have provided interesting outcomes regarding how the MPMAS model component reacts to trends of shifts in fieldwork timing and yield courses. Moreover, all the scenarios were subject to a common uncertainty analysis following the Sobol's sequence (50 design points); this allowed to introduce robustness in the results. Indeed, future simulations with the model system MPMAS_XN should consider a larger sequence of uncertainty (80-100 design points) if time constraints allow it.

In this subsection, the focus was given to the analysis of complex farm reorganizational decisions resulting from potential changes in the climatic conditions at the level of a single farm business size. The following subsection of this chapter presents a different dimension of analysis and focuses on obtaining a closer look into how farm reorganizational pathways can proceed as a farm business engages in a growth process, seeks the achievement of economies of size, and faces farm machinery management decisions in light of distinctive time distributions for the performance of weather-dependent fieldwork operations.

3.2 Economies of size in farm mechanization[5]

3.2.1 Introduction

Structural change in agriculture exerts continuous pressure on farm managers to be efficient and innovative. Besides financial pressure and bankruptcies, Breustedt and Glauben (2007) recognize that structural change in West Europe also results from farmers voluntarily leaving farming because of age and health reasons and off-farm income opportunities. Moreover, Troost and Berger (2016) underline the importance of farm succession in the study of structural change in agriculture. These factors typically incentivize farmers to exit agriculture and allow the remaining growth-oriented farm managers to absorb the idle land, reorganize their businesses, and expand their agricultural operations. In 1980 there were approximately 836,500 farm holdings in West Germany managing an average farm size of 14.6 hectares (ha); in 2019, there were 275,000 farm holdings that managed, on average, 60.5 hectares (BMEL, 2019). One of the drivers of this growth in farm size is the capacity to achieve economies of size (Happe et al. 2008) caused by decreasing average costs for expanding farms. Nevertheless, the extent to which economies of size can be attained and exploited by growth-oriented farm managers depends significantly on their capacity to make full use of their resources, especially the use of farm machinery and equipment, given their nature as non-divisible factors of production.

Decisions on farm machinery use and acquisition play a crucial role in the formation of the cost structure. Farm machinery selection has been acknowledged as one of the most challenging problems in farm management (Søgaard and Sørensen, 2004; Kay et al., 2004), and in order to maintain competitiveness and profitability, farmers are required to invest in the optimal machinery portfolio. Adequate and efficient machinery management allows farmers to acquire and use the proper technological capacity for field operations in the available time windows and is critical for maintaining competitiveness.

[5] A previous version of this subchapter was submitted and accepted as a conference paper at the 10th International Congress on Environmental Modelling and Software iEMSs, under the title: Digital Support for Farm Investment Decisions: Climate Change and Economies of Size in Farm Mechanisation (Mendoza Tijerino et al., 2020).

Moreover, climatic change may fundamentally change the conditions in which farming takes place. Besides increased temperatures and altered precipitation patterns, it increases uncertainty due to increased climate variability and more frequent extreme weather conditions (Olesen et al., 2011; Reidsma et al., 2010). Historically, farmers have always been facing weather variability and are used to the adaptation to climatic conditions; yet, the ongoing rate and intensity of the current changes represent more significant challenges for farm managers (Hatfield et al., 2014; Doll et al. 2017; Lengnick, 2015). While changes in crop yields and production risks may alter crop variety, plant, and soil management as well as the choice of machinery employed, there is an even more direct link between climate and farm machinery management: Fieldwork is time-sensitive. On the one hand, it needs to be realized at defined stages of plant development or quickly react to pest pressure. On the other hand, many fieldwork types depend on good weather and soil conditions suitable for passing with machinery. For example, cereal harvest requires low humidity, and grass hay preparation requires persistence of dry conditions over several days.

The expected warmer conditions resulting from climate change developments may not only alter the timing of fieldwork due to shifts in the growing season and phenological plant development but may also alter the amount of days with suitable weather (Kukal and Irmak, 2018; Olesen and Bindi, 2002; Menzel and Fabian 1999). As Troost and Berger (2015) showed, considering the non-yield effects of climate change such as changes in these "fieldwork days," is essential to understand adaptation decisions in farm management. Farmers can adapt their crop management strategies to cope with tighter or exploit wider time windows, respectively. Consequently, they need to readjust their machinery portfolio to increase fieldwork capacity or save resources using smaller equipment. Doll et al. (2017), for instance, report the need of revised machinery portfolios among farm managers in U.S. Midwest as a result of changes in weather conditions: Due to reduced available days suitable for seeding operations in spring, farmers are investing in larger equipment in order to perform fieldwork operations more efficiently and be able to complete their field operations in time.

Mathematical programming models have a long tradition as scientific tools to understand and optimize farm management, capturing the complex interdependencies between production options, time and resource availability, and taking into account individual farmer objectives (Berger and Troost, 2012). So far, such models have typically either explicitly focused on one type of machinery in particular or have represented fieldwork capacity by distinguishing aggregated typical machinery packages or technology levels rather than a comprehensive collection of available machinery and possible equipment combinations.

In this subchapter, mathematical programming is employed to examine agent investment decisions on machinery and equipment across a wide range of farm sizes in two distinctive climate scenarios that define the current and future availability of weather-dependent fieldwork days. The fieldwork day distributions in both scenarios are based on estimations by the *Kuratorium für Technik und Bauwesen in der Landwirtschaft* (KTBL, 2010), a member-governed agricultural sector organization affiliated with the German Ministry of Nutrition and Agriculture.

According to KTBL (2010), the region of the Central Swabian Jura in Southwest Germany is located within the geographical limits of KTBL climate zone 4. The region is characterized by relative harsh climatic conditions for agricultural production; it has an average yearly temperature of 6 degrees Celsius and is prone to night frost even in summer months. The fieldwork day distribution estimated by KTBL for climate zone 4 is expected to appropriately capture the time windows for weather-dependent fieldwork operations that are currently observed in the Central Swabian Jura.

By comparing a reference period of 1971-2000 to the simulated periods between 2021-2050 ("near future") and 2071-2100 ("far future"), the model ensemble of regional climate projections ReKliEs-De (Hübener et. al., 2017) suggests a much warmer climate for Germany under the business-as-usual scenario (RCP8.5). Furthermore, the climate projections of the ReKliEs-De model ensemble suggest that within the next 35-40 years the climate in the Central Swabian Jura might correspond to the current KTBL climate zone 7 in terms of mean temperature, length of growing period and number of frost and heat days.

Therefore, to assess the potential effects of climate change in the achievement of economies of sizes and optimal farm machinery acquisition, the whole-farm optimization model is run, evaluated and compared across KTBL climate zone 4 ("current" climate in the Central Swabian Jura) and KTBL climate zone 7 ("future" climate in the Central Swabian Jura).

The whole-farm optimization model further considers a broad collection of available sizes for required machinery for arable farming from the comprehensive database of KTBL. The model can flexibly select combinations of aggregates (implement and tractor power) from the available portfolio in its database to minimize overall production costs. The model is applied for the analysis of optimal machinery combinations for different farm sizes, in this way, revealing the information on economies of size implicitly contained in the KTBL data and complex interactions between the use of farm resources.

3.2.2 Data and Methodology

Data

KTBL maintains a comprehensive and regularly updated dataset on crop and livestock production processes, including typical production plans, prices, input costs, and required fieldwork under a variety of production systems (e.g., conventional and organic production, plowing, low tillage or non-tillage, input intensity) (KTBL, 2020).

Besides, the dataset comprises technical data for more than 5,000 fieldwork processes and more than 2,400 machinery and equipment types, including investment and repair costs, lifetime, life use, and fees of farm machinery, as well as data on fuel consumption, tractive power, and time demand of fieldwork operations (distinguished by soil resistance, plot size and plot distances to farmstead). This extensive collection of data allows detailed representation of machinery and fieldwork options in modeling at the farm level. Moreover, the availability of suitable days for performing weather-dependent field operations is based on KTBL estimates for each half months of the growing season. The estimations are distinguished by sensitivity levels for fieldwork types and soil resistances (light, medium, and heavy) across 12 subzones and their likelihood of occurrence (60, 70, 80, and 90 percent) (KTBL, 2010). For the current analysis, the fieldwork day distributions of KTBL climate zones 4 and 7 are evaluated; in general, climate zone 7 depicts a relative higher availability of fieldwork days for weather-dependent field operations than KTBL climate zone 4.

KTBL directly provided a part of the data for the year 2017 for conventional tillage cultivation systems. The database for low tillage cultivation system was obtained by directly connecting to the web applications of KTBL employing an automatized Python script (v 3.5.6) that performed web-scrapping routines. The automatic script is provided in the supplementary materials of this doctoral thesis.

3.2.3 Approach: Farm planning model under distinctive climate zones

A whole-farm inter-temporal planning model was built using mixed-integer mathematical programming (MIP) to determine optimal machinery investment levels and farm managers' operation decisions with several farm sizes and across two KTBL climate zones. The optimization algorithm solves a typical trade-off problem between capital and labor intensities: Larger machinery has higher investment cost and fuel consumption per-use-hour, but also higher area-per-hour working capacity and hence lower labor demands per area unit. Furthermore, machinery is an indivisible asset leading to potential economies of size. Machinery and labor use are constrained, among other factors, by available time windows for the performance of field operations, which may differ between climatic zones.

The model was implemented using the modeling package Mathematical Programming-based Multi-Agent Systems (MPMAS) (Schreinemachers and Berger, 2011). The new MPMAS version in which the model was constructed enables explicit multi-period planning. All the optimizations were run employing the Sobol's sequence (150 design points) for uncertainty analysis (Tarantola et al. 2012) . Furthermore, the optimizations were run with the resources of High Performance Computing (HPC) of Baden Württemberg bwHPC computing facility.

The optimizations performed in this subchapter employ the MIP- based decision model component of the MPMAS software. A comparative-static model evaluation is established between the KTBL climate zones 4 and 7 that represent current and future climate in the Central Swabian Jura.

3.2.4 Model Structure

Overview

A full description of the model structure is provided in the documentation section of this thesis in chapter six. Here, an overview of the structure is presented.

In the current model configuration, a cash balance accounts for cash expenditures and revenues in each year over the planning horizon. At the start of each planning period, cash is spent when investing in new machinery or equipment, fees of owned machinery, buying fuel, hiring labor, hiring fieldwork services from service providers, or paying a debt to any loan. Cash inflow consists of money earned from crop production or received farm support (Eropean Union direct payments). The decision problem's assumed objective function is to maximize the discounted final wealth at the end of the planning horizon of ten years.

The final wealth consists of the accumulated cash earnings from crop production, the residual value of machinery and equipment owned at the end of the planning horizon, and as a negative component, the remaining debt at the end of the planning horizon. For the present analysis, crop areas' choice is not left to the optimization process, but a typical crop rotation has been pre-specified consisting of a low tillage cultivation system of winter rapeseed, winter wheat, and winter barley, each covering and requesting 1/3 of the arable area in each year. On this basis, the optimization problem solves for the best machinery portfolio and associated fieldwork activities.

Each crop management plan requires certain types of field operations at specific times of the season. This fieldwork demand can be satisfied selecting from predefined fieldwork activities, which represent doing a specific type of field operation with a particular equipment combination (e.g., harrowing with a 2 meters-wide rotary harrow and an 83 kW tractor or harrowing with a 4 meters-wide rotary harrow and a 233 kW tractor). The amount of work that can be performed with the acquired machinery and equipment is constrained by the number of equipment and tractors units, as well as available labor and the number of days suitable for performing the fieldwork task. The tractor, equipment, and labor capacities are calculated by multiplying the number of field days for each weather sensitivity level and each half-month with the units of equipment available and their maximum daily hours of use.

Figure 3.11 presents the general structure of the optimization model: The crop areas of winter wheat, winter barley are requested and need to be produced in a way that the best fieldwork activity is chosen among the considered options to perform fieldwork operations; for example, the optimization problem can decide to cultivate one crop with, e.g., a 3 meters-wide cultivator (*Grubber*) and a 45 kW tractor, to sow another crop with, e.g., a 3 meters-wide seeding equipment and also a 45 kW tractor, and, to perform stubble cultivation of the third crop with a cultivator of 3 meters-wide and employing an 83 kW tractor. The associated machinery, equipment, and labor units that provide working capacity need to be available through their acquisition in the market and these provide time capacities (based on the number of field days for each weather sensitivity level half-month and the units of production factors available together with their maximum daily hours of use). Finally, the optimization problem recongVinces that producing the requested crop area by selecting any specific combination of fieldwork activities derives in costs and revenues which are accounted in financial balances.

3.2.5 Experimental Design

Control of Parameters in the Model

To assess economies of size exploitable from optimal investments in an optimal machinery portfolio, the optimization model was evaluated for 20 farm sizes that range from 60 to 630 hectares. The model determines the optimal machinery portfolio to be acquired for the predefined production plan of winter wheat, winter barley and winter rapeseed at each evaluated farm size. To estimate economies of size, no initial machinery endowment was assumed on the farm. To evaluate the impact of the availability of fieldwork days on economies of size, the optimizations were compared for two distinctive climate zones for which KTBL (2010) provides estimates of available fieldwork days in each half month of the growing season (KTBL climate zone 4, representative of cooler, mountainous regions

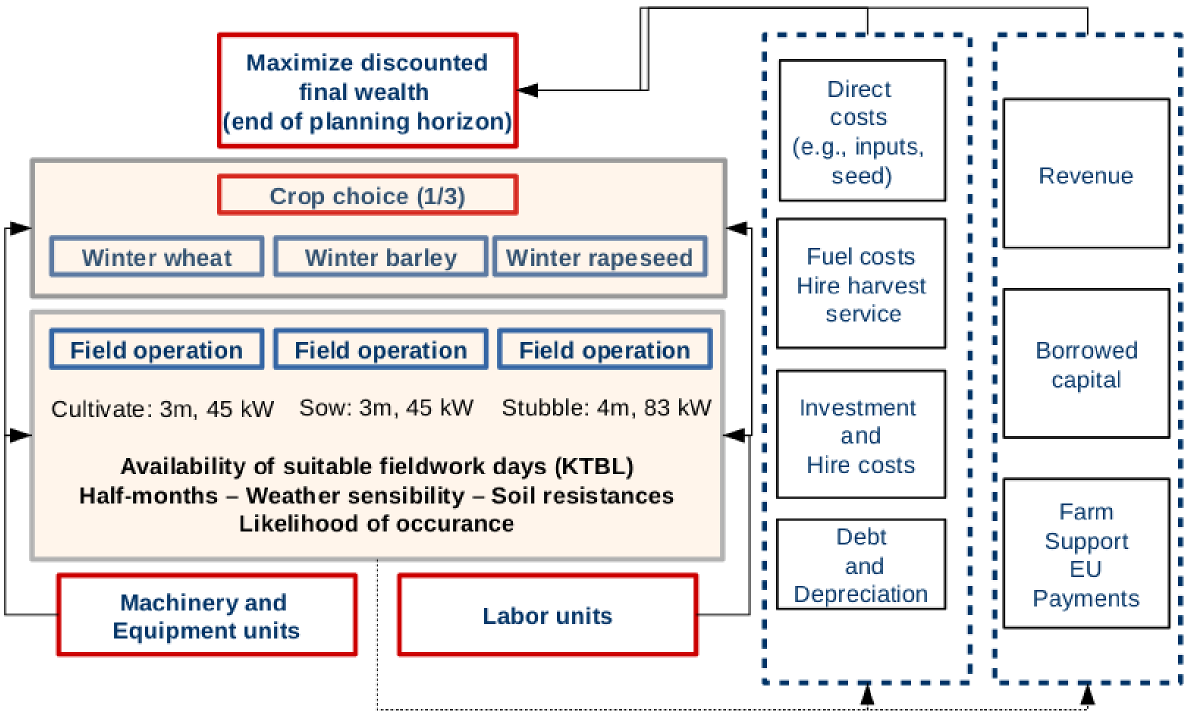

Figure 3.11: *Structure of the optimization model for the analysis of economies of size in farm mechanization*

such as the Swabian Alb, and KTBL climate zone 7 representative of warmer climate).

By considering all weather sensitivity levels for fieldwork types and a medium soil resistance level, figure 3.12 shows the difference of available fieldwork days between KTBL climate zone 7 and KTBL climate zone 4. KTBL climate zone 7 depicts a higher availability of fieldwork days than those estimated by KTBL for climate zone 4; the second half of May (MAI1), the second half of June (JUN2), the second half of July (JUL2) and August (AUG1, AUG2) are the time frames with the most impostant differences across KTBL estimates of available fieldwork days for farm operations.

To isolate the effect of differences in the availability of fieldwork days, it is assumed that no yield differences or alterations in the fieldwork timing (i.e., shifting of the ideal time for fieldwork operation from one half month to another along the planning horizon) between the two climate zones arises. The optimizations were established considering a 10-year planning horizon, a lane distance of 24 meters and a choice of KTBL standard plot configuration of 5 hectare size, a 5 km barn-field distance and high level yield cropping activities on a medium soil resistance level. The uncertain model parameters include the machine and labor working hour limits per day, the terminal value coefficients for acquired assets (machinery), the wage of hired workers, the interest rate for loans, the price of direct inputs, harvesting hiring rates per hectare and fuel, the factor that controls the availability of harvesting hiring services, the interest rate of short-term deposits, the discount rate (time preference of the optimized farm manager) and the length of the loans that can be acquired. The optimization runs were performed for 150 design points of the Sobol's sampling in order to consider uncertainty in all the presented and uncertain model parameters listed above. An overview of the design of the uncertainty analysis is found in the documentation section of this document in chapter six.

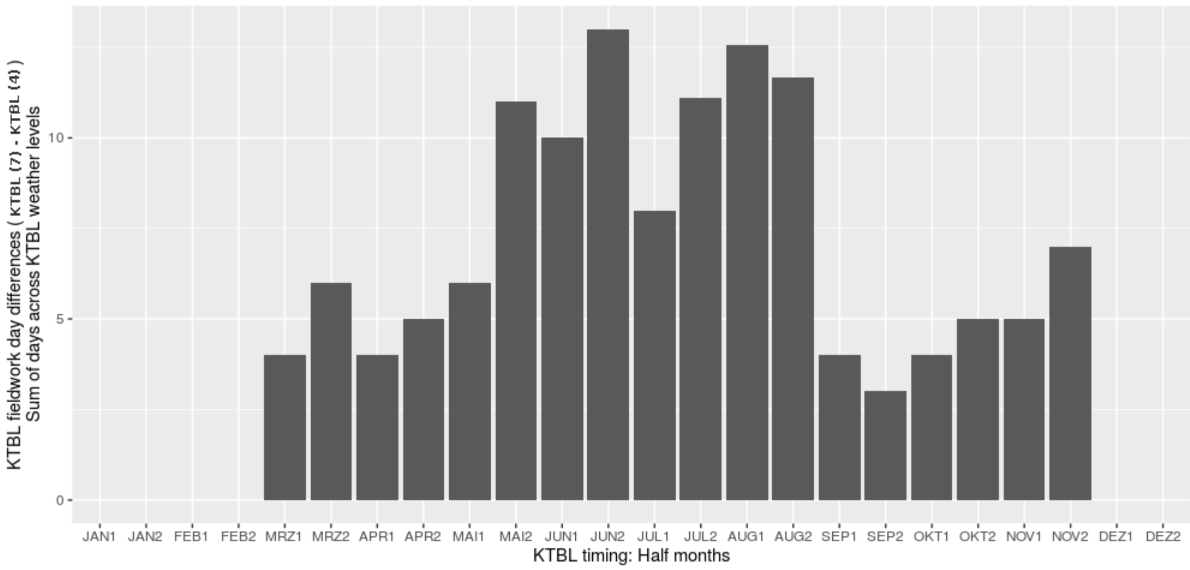

Figure 3.12: *Fieldwork day differences between KTBL climate zone 7 and KTBL climate zone 4. Source: Based on KTBL (2010)*

3.2.6 Results

Return to own labor and cost curves

Figures 3.13 and 3.14 show the optimization results for i) the average yearly return to land and household labor and ii) the average yearly total cost (variable and fixed costs) over a 10-year planning horizon. The results for each figure are shown for the two compared climatic scenarios (KTBL zones 4 and 7) and 150 design points of the uncertainty analysis performed with the Sobol's sampling procedure.

The results indicate that relative gains from farm size expansion can be realized up to 180-210 hectares. It can be observed that the courses of the median and the interquartile ranges of the yearly per-hectare returns (to land and own labor) flatten faster in the scenario with tighter fieldwork time windows (KTBL climate zone 4), leading to an average per-ha difference of approx. 6 percent compared with the scenario with wider time windows (KTBL climate zone 7) in the curve's stable plateau segment. The results show that the scenario with tighter time windows for weather-sensitive field operations is associated with higher per-hectare costs and lower per-hectare returns.

Investments in machinery and equipment

Figure 3.15 presents the model's results on initial investment and the replacement costs for machinery and equipment for a ten-year planning horizon. The results are presented as monetary values (Euros) per hectare for each evaluated farm size. It is possible to observe that the initial investment and accumulated replacement costs per hectare decrease for both of the evaluated climate zones as the farm sizes increase between the farm size ranges of 60 and 240 hectares and remain relatively stable for larger farm sizes. Furthermore, the figure 3.15 reveals that at small farm sizes (e.g., 60-120 hectares), the two climatic scenarios do not result in important differences in investment and replacement costs. More

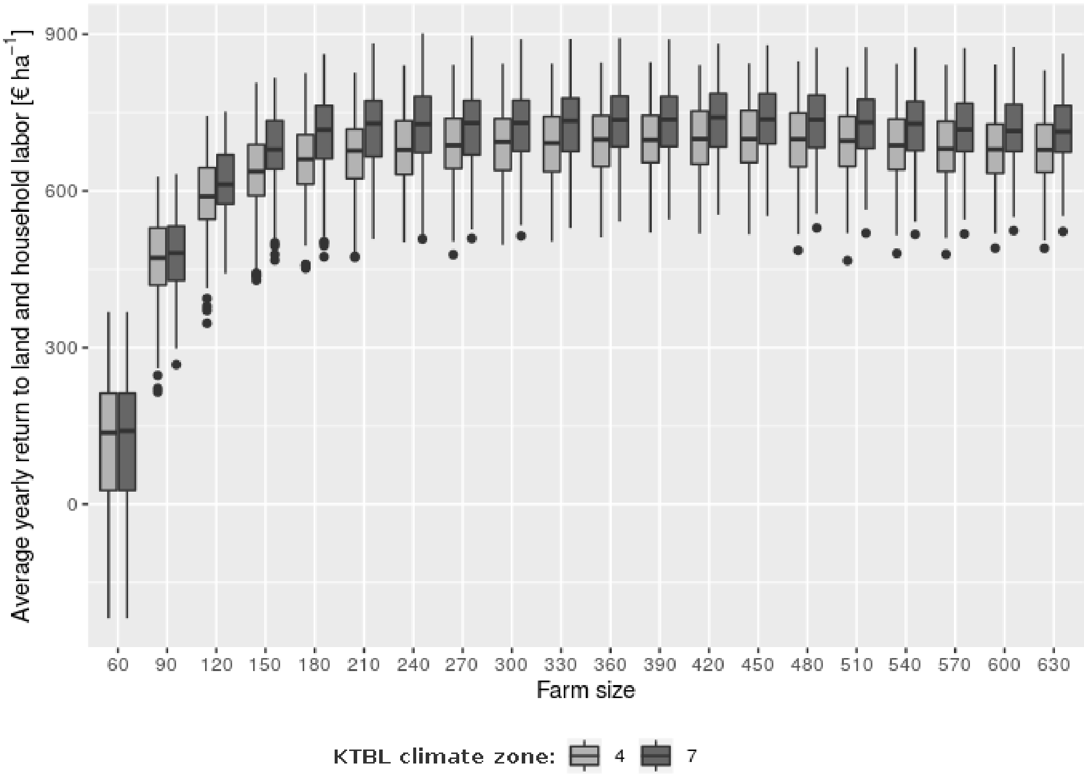

Figure 3.13: *Average yearly return to land and household labor. Values in Euros per hectare. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence.*

significant differences can be observed at farm sizes in the range of 240-480 hectares, where the median investment and replacement costs on machinery and equipment are somewhat higher in the climatic scenario with tighter time windows for field operations. A higher difference in the median investment and replacement costs on machinery and equipment between climate zones is observed at farm sizes in the range of 510-630 hectares.

Figures 3.16 and 3.17 show optimization results that reveal emerging patterns in the acquisition of machinery and equipment types. For an illustration of the resulting machinery acquisition trends, the figures show the acquisition patters of two types of technologies: Seeding equipment and tractors at all their optimally acquired specifications in accordance with the model's database. The acquisition patterns for all the different types of combined harvesters, cultivators, rotary harrows, crop protection sprayers, and centrifugal spreaders, are presented in the annexes section of this document in chapter six (Figures: 6.9, 6.10, 6.11, 6.12, 6.13, 6.14). The results shown in annexes are also displayed across all the evaluated farm sizes and climate zones. The y-axis shows the technology's size or capacity level, and the x-axis the farm size.

The figure 3.16 reveals that larger farm sizes are associated with a demand for larger seeding equipment; the figure shows that for the evaluated sizes between 570 and 630 hectares, most of the design points of the uncertainty analysis at which the optimization model was evaluated resulted in the acquisition of the largest available seeding equipment specification contained in the used database version (six meters wide). In contrast, in small farm sizes (e.g., 60-120 hectares), the majority of the design points of the uncer-

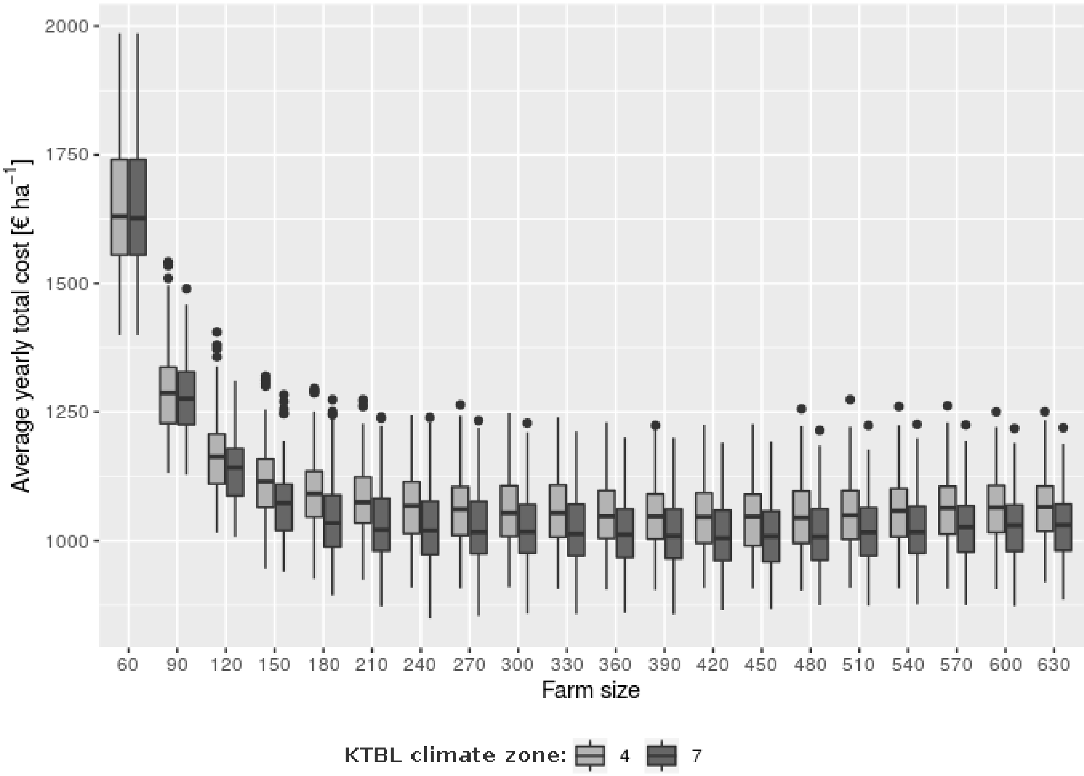

Figure 3.14: *Average yearly total cost (variable and fixed costs). Values in Euros per hectare. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence.*

tainty analysis resulted in optimization outcomes where the acquisition of the smallest available seeding equipment specification (two meters wide) was optimal. Furthermore, the optimization results show that at farm sizes between 180 and 524, several combinations of equipment types can potentially arise. For example, farm sizes between 270 and 300 hectares are associated mostly with a demand for 4-meter seeding equipment, but results for further farm size increases show that combinations of other equipment sizes are also an optimal strategy. For instance, at 390 hectares in both evaluated climate zones, the optimization results indicate that there are potentially various combinations of equipment sizes that can be optimal (6, 4, 3, and 2.5 meters) depending on the uncertainty sampling point that is considered.

Figure 3.17 shows the optimal acquisition of tractors for each mechanization level considered in the model's database. It is possible to observe that small farms (e.g., sizes between 60 and 180 hectares) are associated with the acquisition of the three smallest mechanization levels (37, 45, and 54 kW) in both of the evaluated scenarios of KTBL climate zones. Tractors that provide 83 kW are demanded across all the farm sizes evaluated. The figure also reveals that large farms show the potential to acquire several tractors that provide the highest mechanization levels (e.g., 138 and 200 kW) across the Sobol sampling points for uncertainty.

Two main messages can be drawn from the illustrations depicting the trends in machinery acquisition. First, and as expected, larger farms are associated with a demand for bigger and higher capacity equipment than smaller farms. This observation partic-

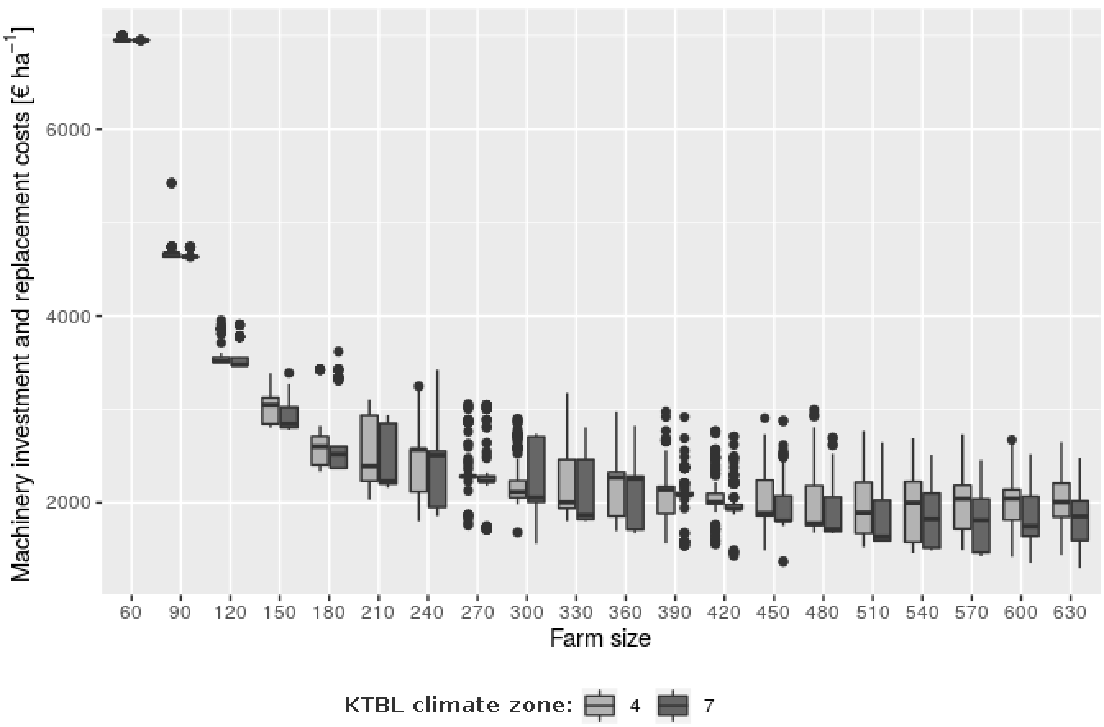

Figure 3.15: *Initial investment and replacement costs for machinery and equipment over a 10-year planning horizon. Values in Euros per hectare. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence.*

ularly holds for equipment types like cultivators, rotary harrows, tractors, and seeding equipment. Other types of equipment, such as crop protection sprayers and centrifugal spreaders, were demanded at their medium and high capacity specifications across small and large farm sizes (e.g., 60-120 hectares and 600-630 hectares).

Second, even when larger farms tend to acquire larger equipment, the evaluation of a broad range of farm sizes in the optimization model reveals that the demand for particular types of small and medium-sized equipment can follow a bimodal distribution. For example, this trend can be observed for seeding equipment and rotary harrows of 2,5 and 3 meters-wide, cultivators of 3 and 4.5 meters-wide, combined harvesters of 125 and 150 kW, or crop protection sprayers of 1,500 liters. In this way, the optimization results allow observing different machinery acquisition thresholds across all the farm sizes evaluated.

Figure 3.18 shows the excess of machinery-use capacity[6] of the acquired seeding equipments of two-meters for the evaluated farm sizes. The excess of machinery-use capacity is measured as the difference between the supply of available hours for fieldwork activities (fieldwork days times machinery working hours per day and amount of units of equipment acquired) minus the demand for fieldwork hours to conduct the required operations. The figure is shown for the specific half month of the year in which the field operations are conducted (horizontal axis) and the weather sensitivity levels associated with the fieldwork (vertical axis). The figure 3.18 reveals a decreasing trend of the median excess

[6]Presented for the design points where there is an above-zero acquisition of units of the evaluated equipment.

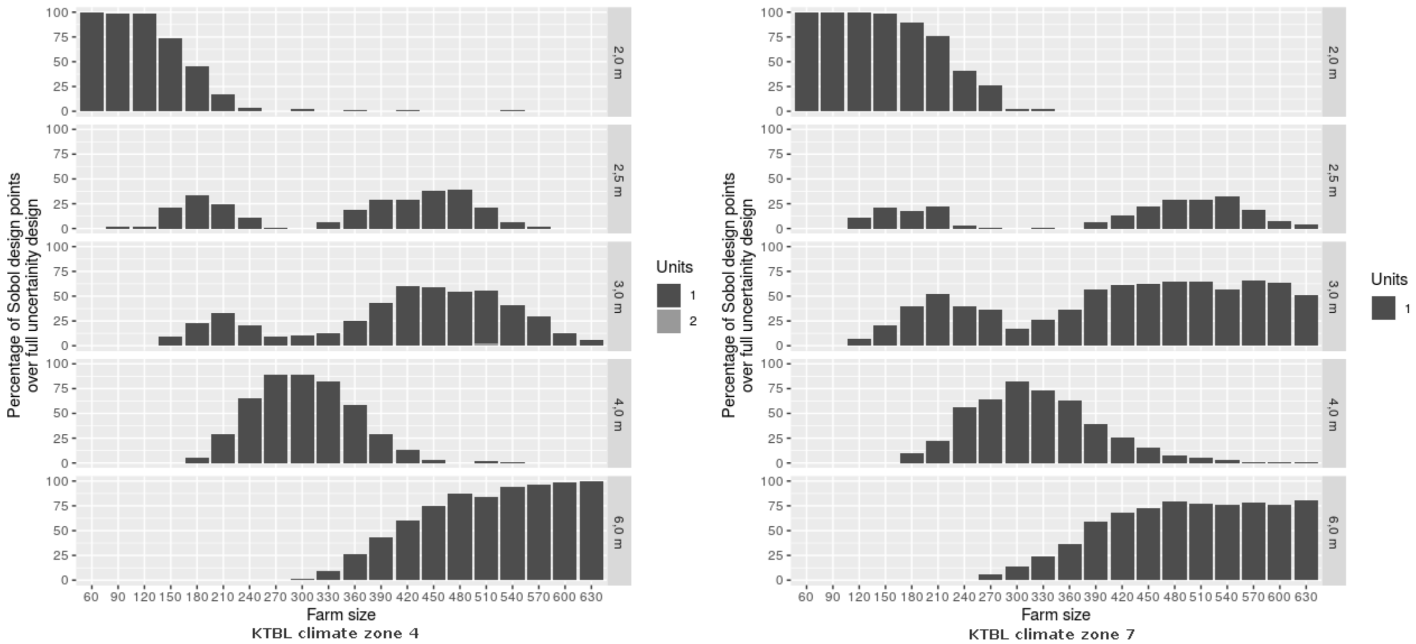

Figure 3.16: *Machinery and equipment acquisition: Seeding equipment. Percentage of Sobol's design points where each equipment type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence.*

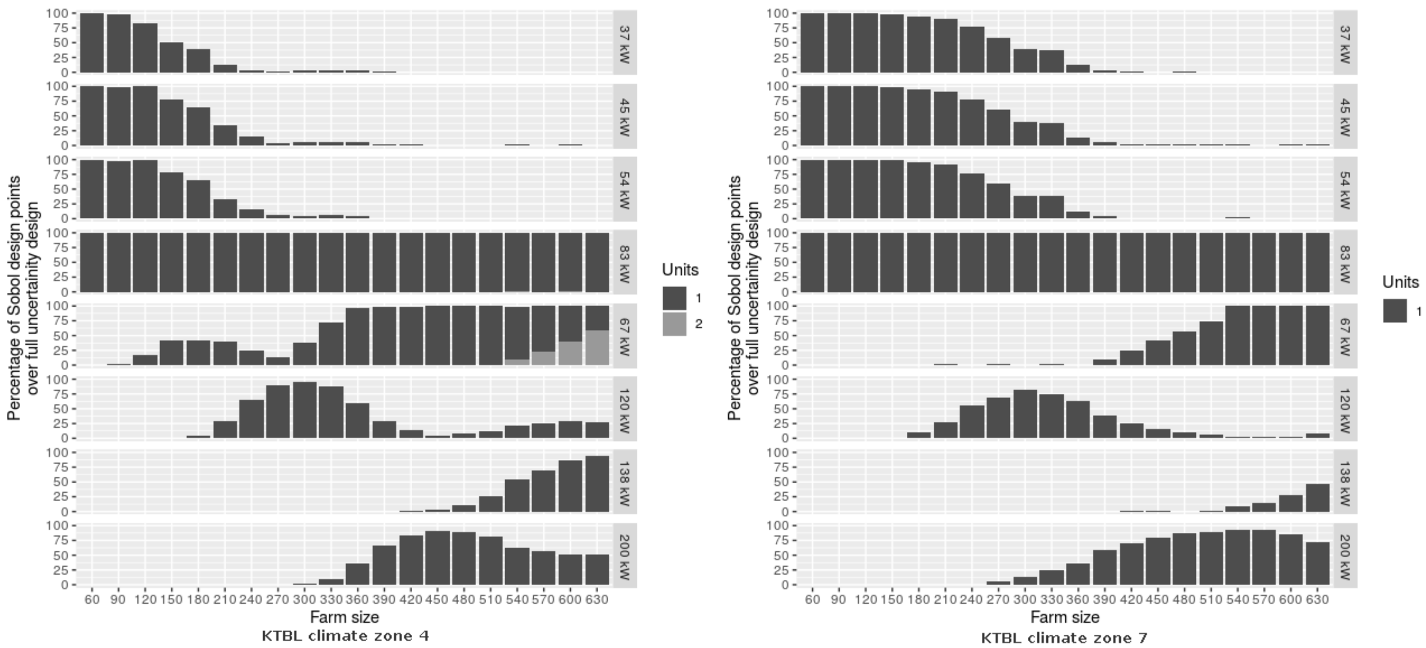

Figure 3.17: *Machinery and equipment acquisition: Tractors. Percentage of Sobol's design points where each tractor type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence.*

of machinery- use capacity as the farm size increases; as the farm sizes get larger, the equipment is used more time while approaching to the frontiers of its time capacity provision. Figure 3.19 shows the excess of machinery-use capacity for a piece of six-meter seeding equipment for comparison purposes. Alternatively, figures 3.20 (KTBL climate zone 4) and 3.21 (KTBL climate zone 7) show the excess of machinery-use capacity of the acquired 200 kW tractors at the evaluated farm sizes. The figures are shown for the specific half months of the year in which this type of tractor is used for fieldwork activities requiring a 200 kW mechanization level (half months are shown this time in the vertical axis). Furthermore, weather sensitivity levels five and six are distinguished (this time in the horizontal axis). Figures 3.20 and 3.21 reveal that the excess capacity varies greatly across the different points in time and the evaluated KTBL climatic scenarios. This variation of excess capacity for the acquired 200 kW tractors was also observable in other tractor specifications.

The figures 3.18, 3.19, 3.20, and 3.21 show a broad variation in the courses of the excess capacity of equipment and machinery. For instance, when a single equipment specification is used over several farm sizes with no alternative machinery combination, the excess of machinery use capacity tends to decrease: For example, between farm sizes 60-180 for the case of the seeding equipment of two meters wide. Notice that this result is consistent with the seeding equipment demand at these farm sizes shown in 3.16, where the two-meter wide seeding equipment is the common equipment used for sowing operations between 60 and 180 hectares. When several machinery specifications can be employed to perform fieldwork activities (e.g., using one 3 with and 6-meter wide seeding equipment to complete a task, or a 45 and 37 kW tractor), different trends for the excess of capacity can arise. Figures 3.20 and 3.21 display this observation: The half-month number 16 (first half of September) in the figure 3.20 shows that the median excess of machinery use capacity for a 200 kW tractor decreases significantly at the largest farm sizes (540-630 hectares) in comparison to smaller farm sizes. However, in figure 3.21 shows that the median excess of machinery use capacity remains fairly stable at the same farm sizes with 540-630 hectares. These developments can be tracked down when one observes the trends in tractors' acquisition; in the KTBL climate zone 4, there is a different tractor acquisition pattern than in KTBL climate zone 7. At the farm sizes with 540-630 hectares, the optimizing farm agent shows a much higher demand for a tractor with a lower mechanization level (138 and 67 kW) in KTBL climate zone 4 than in 7. A presentation of the excess of the machinery-use capacities derived from the optimization results for cultivators, rotary harrows, crop protection sprayers, and centrifugal spreaders is provided in annexes.

Hiring of fieldwork operations and labor

Figure 3.22 presents the average yearly demand for permanent workers (with a 25 percent position) over a ten-year planning horizon for all the evaluated farm sizes. The demand for labor capacity is usually higher for KTBL climate zone 4, indicating that tighter time windows for field operations require an optimal combination of higher-value machinery and higher labor utilization than for climate zone 7 (with looser time windows). Furthermore, in figure 3.23 it is shown that, as farm sizes increase, harvesting operations are performed by combining the use of acquired combine harvesters for a part of the cultivated area and hired services for the remainder. Hiring services do not compromise the farm's labor capacity, whereas utilizing combine harvesters saves payment of hiring fees but increases the demand for labor capacity. Decisions about using harvesting equipment or hired services are dependent on whether the constraint representing the maximum expected supply of hiring services becomes binding, how fully utilized the contracted labor can be at each farm size, and on the overall profitability of using either of the alternatives for harvesting operations.

3.2.7 Discussion

The optimization results shown in the previous section indicate the inherent existence of economies of size in machinery choice contained in the KTBL database. The marginal effect of farm size increases on per-ha farm costs and returns to own labor and land flattens out for larger farm sizes. In the optimization results, the flattening out of the cost curve per hectare at medium to large farm sizes (e.g., 240 -600 ha) is the result of increasing absolute total costs that derive from the combined interplay between higher labor costs and regular higher investment requirements for larger equipment and machinery as farms expand. The obtained results allowed to further identify thresholds and potential courses and distributions of machinery and equipment acquisition across the path of expansion of a farm business. An increase in the farm size can initially be associated with a decrease in the demand for low-capacity or small equipment, yet, further farm expansions can result in situations where small or medium-sized machinery and equipment are again demanded since fieldwork operations can be best performed by the combination of several sizes of equipment. This observation can be particularly relevant for the farm equipment industry, where the identification of thresholds for farm machinery and equipment demand can support production planning in the course of agricultural structural change in Germany.

The drawn results hold for the current technologies captured in the model's database. The optimization model's flexibility is also currently limited by the fieldwork – machinery combinations for which KTBL provides fuel use and per-hour working capacity data. While this range is broad, it still sets a boundary within the optimization model operates, and it cannot be ruled out that for certain conditions, a tractor-equipment combination that would not ordinarily be considered adequate and observed in common use might still be efficient as part of a whole farm plan. Likewise, the presented results hold for a high-yield crop level (in middle resistance soils) and the associated variety of machinery combinations at all the mechanization levels suggested for this high yield level by KTBL. Moreover, the presented results are specific to the particular crop rotation determined in the model. While it is a typical rotation in Germany, a different overlap in timing and special machinery required for other crops like maize or sugar beet may lead to different inflection points and responses to availability of fieldwork days. Nevertheless, it is expected that the general shape of the cost and investment curves over the evaluated farm sizes persists.

The results of the optimization model allowed to observe potential effects of current and future climatic conditions on machinery investment costs and economies of size derived from farm mechanization. As expected, the model's output showed that tighter time windows for current weather sensitive fieldwork operations (KTBL climate zone 4) resulted in higher-value machinery acquisition while requiring higher investment (and replacement) costs for the specified and requested crop rotation. However, this effect was not uniform for all simulated farm sizes. Furthermore, the presented results suggest that wider time windows for future fieldwork operations, (KTBL climate zone 7), allow more substantial exploitation of economies of size.

The presented results further indicate that tighter time windows for fieldwork operations are associated with higher labor demand, and this higher demand for labor occurs when higher-value (and more efficient) machinery and equipment are also demanded. An apparent dilemma arises: If higher-value – and therefore, more efficient – equipment is acquired, a decrease in the requirement for labor's work should be expected. For instance, plowing a hectare with a two-shared reversible plow of 0.7 meters wide and 102 kW tractor requires 3.43 working hours, whereas a three- shared plow of 1.05 wide plow powered by the same tractor can perform the work in 2.29 hours[7]. While correct in a simple theoretical example, this view is a naive resolution in the context of a whole-farm planning model, where complex interactions between resources can arise, especially when fieldwork activities are aggregates of technologies that compete for the use of the equipment time capacity and tractor time capacities, which can be employed for alternative activities.

The reason for a general increase in labor demand in the scenario with higher-value machinery acquisition (KTBL climate zone 4) is that the demand for work time associated with the use of particular machinery (e.g., tractor) can increase due to the combined effect of less available time for performing fieldwork operations (KTBL climate zones) and the reorganization of the whole-farm plan. An increase in the time demand associated with the use of one machinery (e.g., tractor) can be independent of the decrease in the time demand associated with the performance of a particular fieldwork operation that uses a more efficient and expensive equipment (e.g., wider seeding equipment).

The decrease in the available days suitable for a field operation (e.g., seeding) in one particular half-month (e.g., the first half of August) can drive the optimization problem to demand higher-value equipment (e.g., a larger seeding implement). But it can also occur that a decrease in the available days suitable for alternative field operations in another half-month (e.g., the second half of September or October) drives the optimizing problem to rather adapt the fieldwork plan in the half-month[8]. The reorganization of the fieldwork plan can result in circumstances where there is a decrease in the use of particular machinery, for example a tractor of 200 kW, because, under the new tighter climatic conditions, a fieldwork task can be best performed by combining two types of equipment or implement, e.g., one implement that requires the power of a 200 kW tractor and another, smaller, implement that requires the power of a lower class tractor that is less occupied but requires to be used for a longer time due to the lower efficiency of the employed implement[9].

The strength of the whole-farm optimization planning model is that it allows the recognition that fieldwork operations can be performed in different half-months. For example, harrowing with a seedbed combination equipment, deep cultivation, stubble cultivation, and seeding can take place at the same half-month of the year and at different intensities (hectare demand). More importantly it is to notice that the fieldwork activities are established as aggregates (equipment size and tractor power that can deal with the equipment's size); employing one equipment that has low efficiency increases the time-demand for the associated tractor operated, resulting in higher demand for time for the work operation as long as the time window allows it.

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[7]Values taken from the online applications of KTBL for a high tillage resistance, a plot size of 5 hectares, and distance farm-plot of 5 km. KTBL-Feldarbeitsrechner.

[8]Id est, adapt the number of hectares to serve with a specific aggregate of equipment/implement and tractor type

[9]A detailed example for a 540-hectare optimization problem of a design point of the Sobol's sequence tracks down and examines the reorganizational adaptation of fieldwork demand as an example supporting this argument. The example can be found in the subsection 6.4.1 in the annexes of this thesis

Accumulated machinery demand in peak times can be overcome by a higher diverse selection of cropping possibilities that allow a diversity of fieldwork schedules. Allowing the model to optimize crop and machinery choice simultaneously has the potential to alter the economies of size relations and the effects of distinctive suitable days for field operations on investment costs, returns, and demand for resources (i.e., labor work). Nevertheless, this is not yet represented in the current model version. Moreover, machinery use is only one of several aspects associated with economies of size in agricultural production. For example, other factors are better prices obtained for a larger volume of sales and purchases, better financing conditions, and relative savings in other overhead costs. Counter-acting aspects may be less managerial supervision per plot and laborer. Other branches of production, e.g., livestock or bioenergy production, may exhibit economies of size that considerably differ from arable crop production.

The optimization model incorporates the hiring of harvesting services from a simple perspective; the model version does not still consider that harvesting services might not be available for the farm agent at the times that they are required, this due to the peak demand of services when the same crops are grown in a small region. Hiring harvesting services may also be associated with the outsourcing of weather-related risks. Considering risk and risk mitigation strategies may lead to more certainty in long-term planning.

The experimental design was established with a fixed plot size and farmstead-to-plot distance for all farm sizes. In reality, travel distances can generally be expected to increase as farms get larger, while plot size might increase as well, although it may depend more on topography and political and cultural history. While not currently considered, these aspects can be examined by repeating the optimizations varying crop rotation, tillage intensity, and other parameters.

The current trend of agricultural machinery supply and innovation is directed towards the development of higher-capacity, higher value, more intelligent, more complex, and more efficient systems (Bochtis et al., 2014). These types of innovations in farm machinery and equipment have the potential to induce a technological treadmill where farmers are forced to achieve a sufficiently large size that justifies the acquisition of the technology to maintain competitiveness (Duffy, 2009). Do farmers in Germany really need to grow? What is the future of small-farm agriculture in Southwest Germany? The existence of larger and more complex farm equipment on the market suggests that there is a demand for it, and such a demand may only be justified in large-enough farm business; these developments pose the question of what is the farm structure that is desired by the society.

Machinery sharing may be an alternative to preserve the farm structure. The extent to which the preservation of the farm structure is desired by society in Germany is not a matter of this work, yet, Chapter 4 provides a framework that can allow related research that helps informing such relevant questions. Chapter 4 discusses the topic of farm machinery sharing and proposes an approach to further enhance the MPMAS modeling tool for representing shared investments in farm equipment. The implementation of an external algorithm is presented, and exemplary simulation runs are shown and discussed.

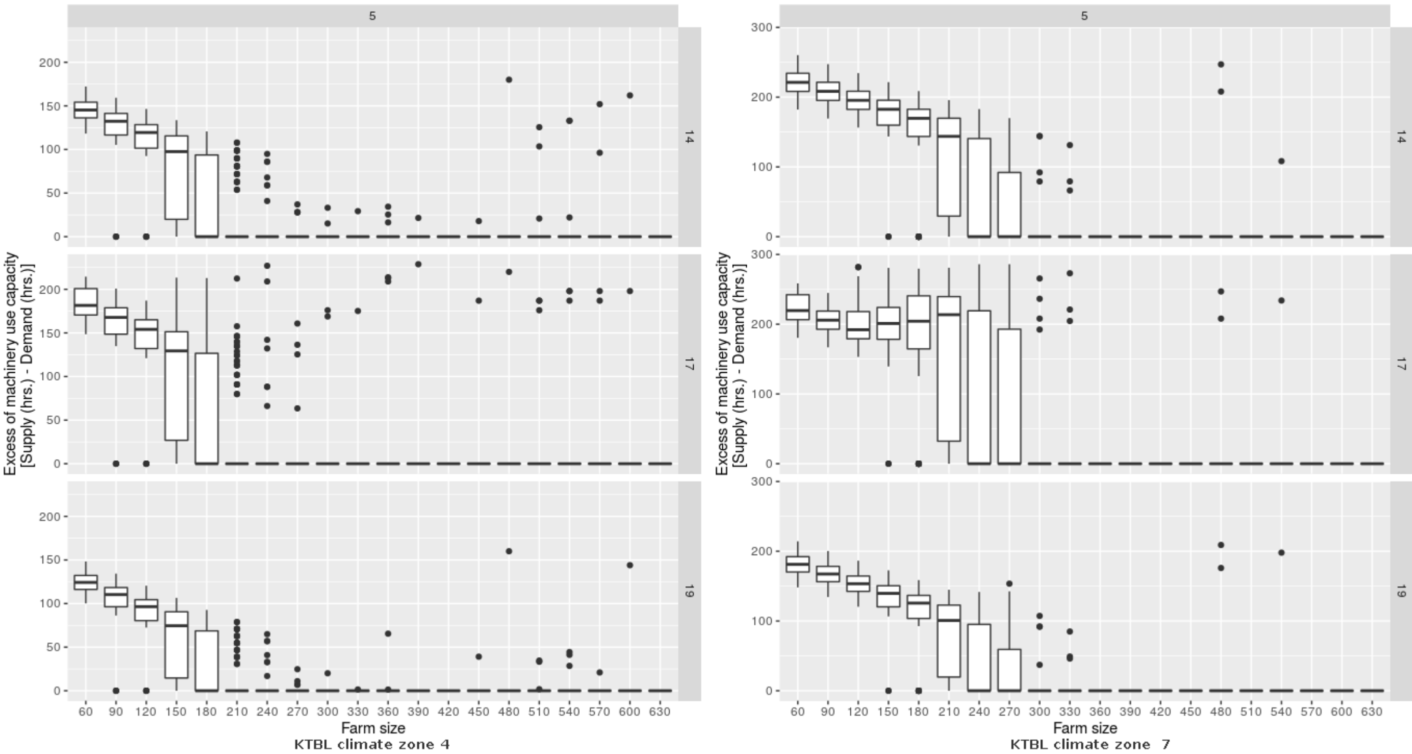

Figure 3.18: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Seeding equipment 2-meters. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis). Half months: 14 (AUG1), 17 (SEP2) 19 (OKT2).*

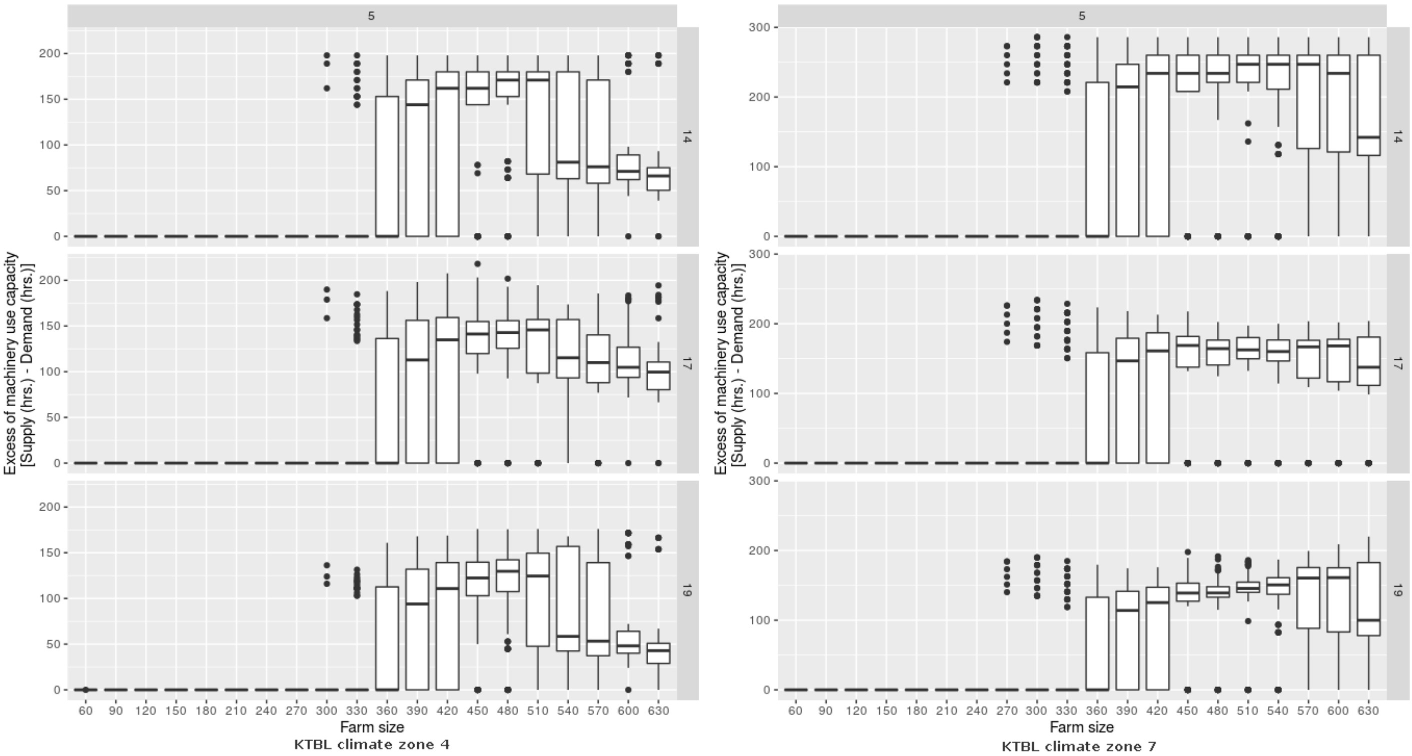

Figure 3.19: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Seeding equipment 6-meters. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis). Half months: 14 (AUG1), 17 (SEP2) 19 (OKT2).*

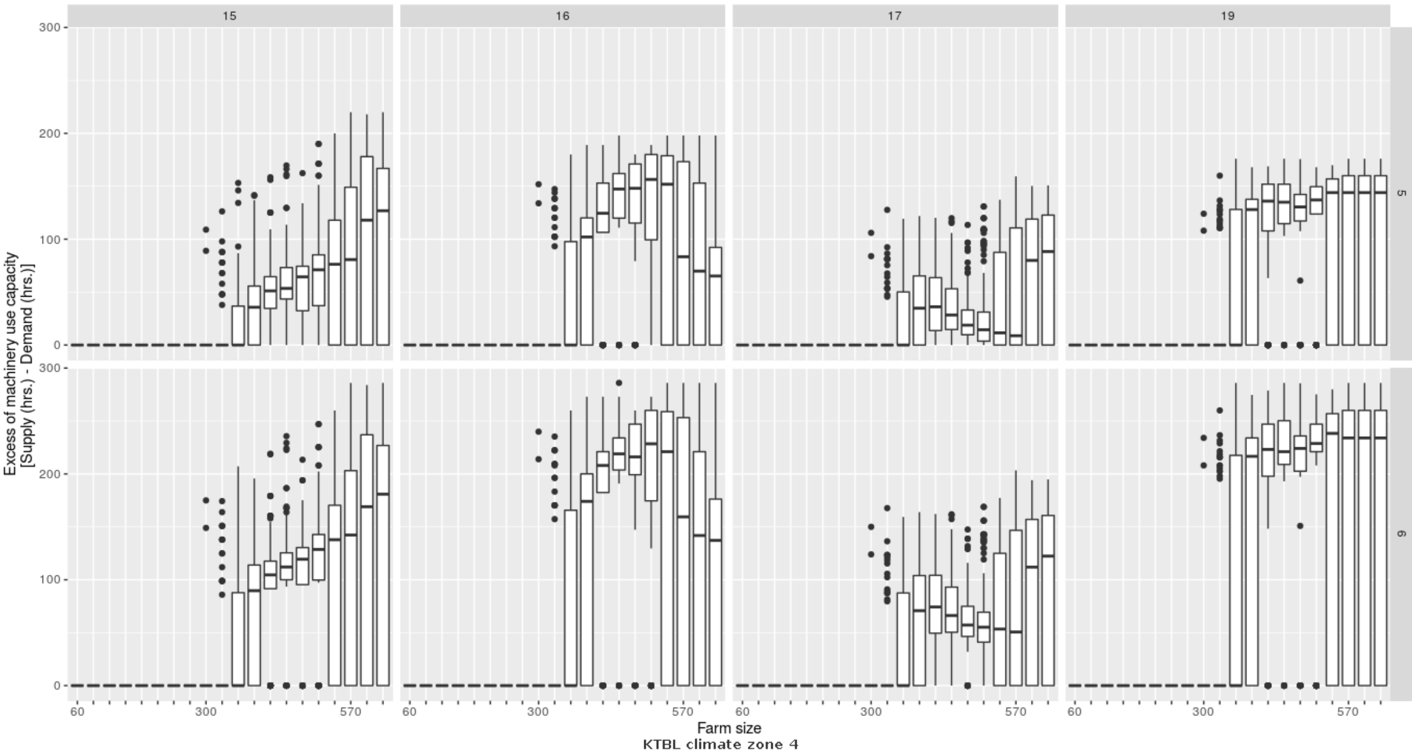

Figure 3.20: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Tractor 200 kW. KTBL climate zone 4. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (horizontal axis), weather level (vertical axis). Half months: 15 (AUG2), 16 (SEP1),17 (SEP2) 19 (OKT2).*

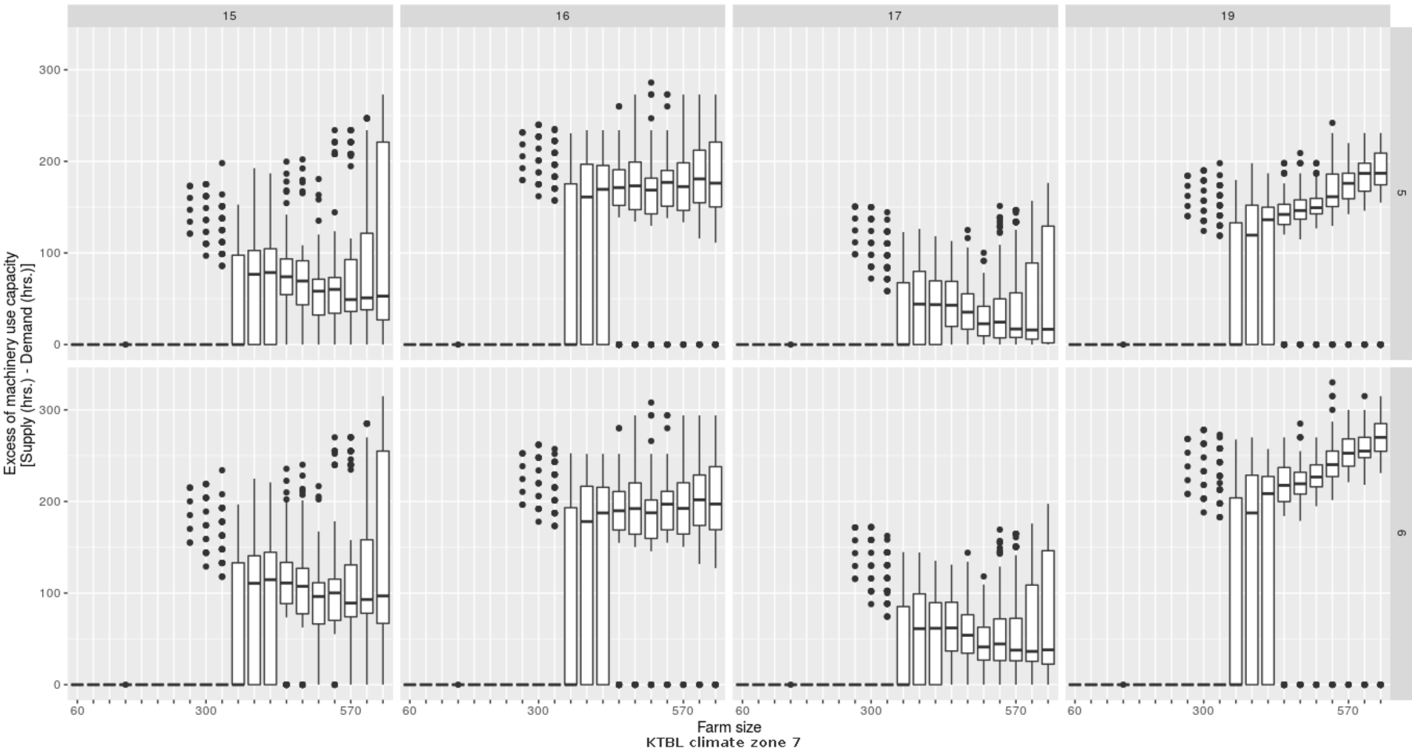

Figure 3.21: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Tractor 200 kW. KTBL climate zone 7. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (horizontal axis), weather level (vertical axis). Half months: 15 (AUG2), 16 (SEP1),17 (SEP2) 19 (OKT2).*

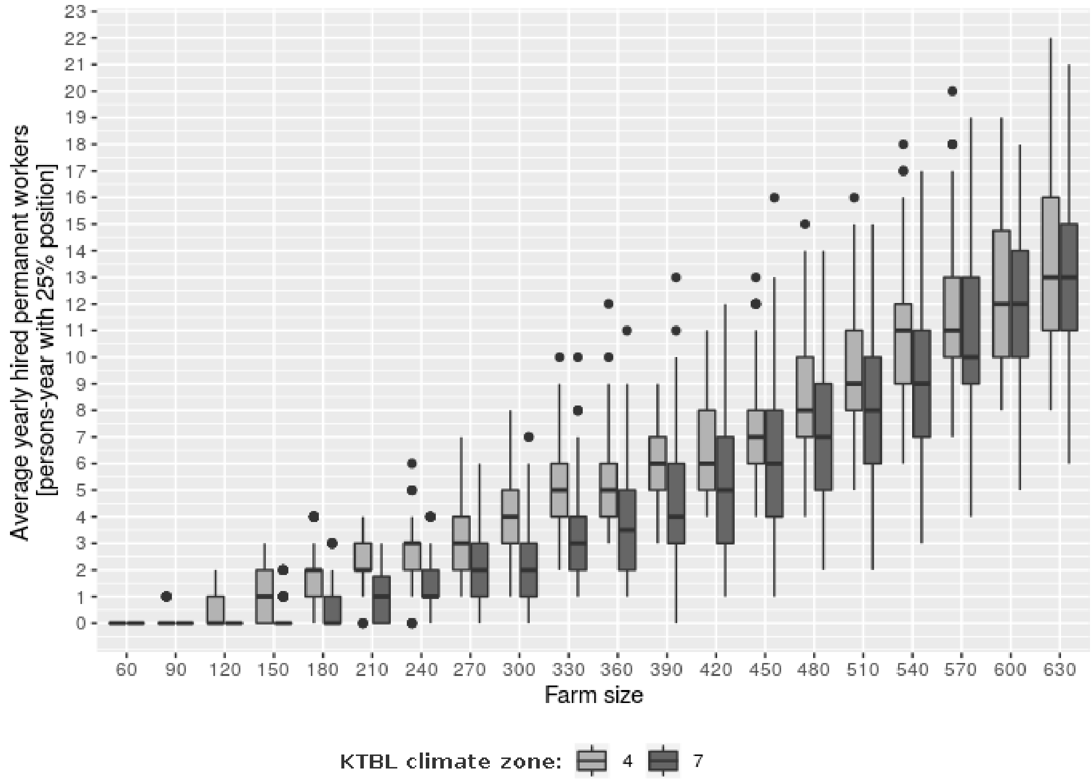

Figure 3.22: *Average yearly hiring of external labor (persons per year with 25 percent position). Average over a 10-year planning horizon. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence.*

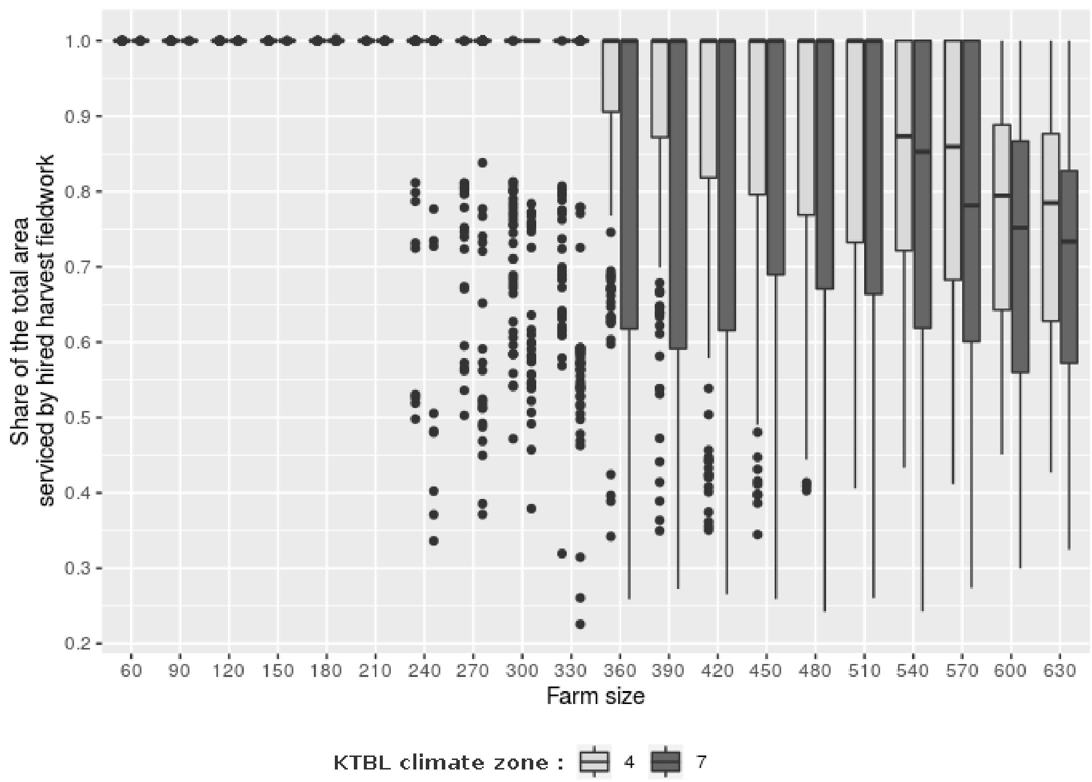

Figure 3.23: *Share of the total arable area serviced by hiring harvesting services. Average over a 10-year planning horizon. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence.*

3.3 Validation

3.3.1 Pre-considerations

In their contribution, Troost and Berger (2020) highlight, that a model validation should be founded on the basis of the context in which it is developed, together with its intended purpose, data availability, and intended conclusions. Furthermore, they argue that a case for validation of simulation models should rest on the basis of three pillars; namely, i) knowledge about system input-output relationships, ii) knowledge about the system process and structures, and iii) robustness of outputs and conclusions.

The question of the appropriate conditions for the adequacy of comparing simulation output with real-world observations (first pillar) should be answered on the basis of an assessment of the quality of the comparison data (variability, quality, and quantity of data-observations), the certainty of the model structure, and the knowledge regarding likely deviations-errors (Troost and Berger, 2020). Moreover, it is necessary and desirable to achieve a comprehensive knowledge about the behavior of the elements within the given and purposefully designed model system (second pillar); the emergence characteristics that arise from the individual, (ideally) well-represented, processes and relationships of the system allow to derive predictions even in situations that are not yet observed (Troost and Berger, 2014; Nolan et al., 2009). As a third pillar, Troost and Berger (2014) highlight the value of an adequate uncertainty analysis as an essential component of good and necessary practices for simulation analysis and validation procedure; the performance of uncertainty analysis ensures that obtained results hold for different combinations of likely ranges of the input values of the model. In situations where model input data is uncertain (due to an intrinsic lack of knowledge or errors in measurements), uncertainty analysis provides robustness to the obtained simulation results.

To assess the quality of the results from the optimizations and simulations performed in this investigation, selected simulated outcomes were compared against real-world outcomes. Nevertheless, this endeavor is challenging due to the own nature of the present doctoral work; through the simulations and optimizations, the focus was placed on two particular elements of the modeled farming systems: Machinery (and equipment) acquisition and economies of size, on the one hand, and land-use dynamics, on the other hand. Detailed information on i) acquisition of machinery and equipment (type of equipment and size) and ii) used aggregates used for conducting fieldwork operations (tractor type and implement type) are rarely gathered in detail and communicated in general surveys for farms in Germany. Instead, general information on the financial results is available for different disaggregations. In the subchapter 3.1, "Dynamic effects of shifts in fieldwork time on land-use and machinery acquisition", the focus was placed on the investment cost on the machinery and equipment portfolio and the simulated crop rotations that derive from the farm agent's optimizing decision. In the subchapter 3.2, "Economies of size in farm mechanization", the focus was placed in comparing observed and simulated outcomes for two indicators: Fixed costs and variable costs, on the one hand, and investment cost on the machinery and equipment portfolio on the other hand.

3.3.2 Dynamic effects of shifts in fieldwork time on land-use and machinery acquisition

The results presented in the subchapter "Dynamic effects of shifts in fieldwork time on land-use and machinery acquisition" were based on an experimental design that explicitly aimed to examine the responsiveness of the Central Swabian Jura MPMAS model to diverse and expected climatic change trends. The model system was designed to capture shifts of fieldwork times. In this Ph.D. work, the focus was on the effect of shifted trends of fieldwork timing and yield courses on land-use and machinery acquisition on an exemplary simulated 150-hectare arable farm. Regarding machinery acquisition alternatives, and in general, farm machinery management, the model represents a broad constellation of the relationships that allows the modeled farm agent to acquire the optimal machinery portfolio in light of not-yet observed climate change manifestations, this, while considering relevant land-use conditions (i.e., crop rotations), policy restrictions, costs, and benefits derived from crop production. The following sections of "Machinery portfolio cost" and "Crop rotations" show that the MPMAS model constructed for the Central Swabian Jura research area predicts well the investment cost on farm equipment and machinery. It also follows the expected crop rotation patterns of the studied region.

Machinery portfolio cost

The State Institute for Agriculture, Food, and Rural Areas (LEL) for Baden Wuerttemberg (LEL, 2020) provides estimates of the cost-valuation of technical equipment, machinery, and other assets for full-time farmers for different farm sizes. Table 3.9 shows this information as values per hectare for the different farm sizes.

Indicator	20-30 ha	30-50 ha	50-100 ha	above 100 ha
Area (ha)	25.39	40.16	70.14	147.20
Arable land (ha)	9.6	20.42	46.16	98.77
Technical equipment, machinery, other assets (€/ha)	2,905	2,305	1,822	1,491

Table 3.9: *Closing balance for valuation of technical equipment, machinery and other assets. Financial year 2018-2019. Source: State Institute for Agriculture, Food, and Rural Areas (LEL) for Baden Wuerttemberg, LEL (2020).*

The Federal Ministry of Nutrition and Agriculture (BMEL, 2020) also provides estimates of the cost-valuation of technical equipment, machinery, and other assets for test (arable) farms. Table 3.10 shows this information as values per hectare for the different farm sizes. The information is provided in terms of business "types", grouped on the basis of thirds of the achieved profit.

The investment cost of the optimal machinery portfolio resulting from the model employed in subchapter 3.1 falls in an expected ranges, when compared to the valuation provided by the public offices (Tables 3.9 and 3.10). The baseline scenario evaluated for 50 design points of uncertainty analysis the model can predict an expected initial investment cost of about 1,000 Euros per hectare (Figure 3.24). This value is fairly similar to what has been observed in terms of technical equipment, machinery, and other fixed assets by

Indicator	Lower third	Middle third	Upper third
Farm businesses (n)	641	602	452
Farm size (ha)	135.4	140.9	174.9
Technical equipment, machinery, other assets (€/ha)	902	774	1,126

Table 3.10: *Book-keeping results of the test farms in agriculture 2018-19. Source: Federal Ministry of Nutrition and Agriculture (BMEL, 2020).*

the public offices and showed in tables 3.9 and 3.10. For this figure, the 50 percent of the initial investment cost was calculated and is presented. The reason for this calculation is that the accounting values provided by the public institutions presented above correspond to acquired assets to which a certain age is unknown. Considering that the book value is equal to the investment cost minus the accumulated depreciation, the expected value from the optimized investment portfolio is estimated in the model results by accounting an average accumulated depreciation of 50 percent of the total initial investment cost.

It should be pointed out that the harvesting operations for silage maize that the farm agent chooses in the current employed model version are performed with a single row, 0.75 meters, corn chopper implement with a 67 kW tractor mechanization level (that can be required by other fieldwork operations). This aggregate specification is considered small in comparison to aggregates used in the typical harvesting operations in the research area. The farm agent uses this aggregate because it corresponds to the most economical fieldwork activity (low cost of the implement) that can manage the harvesting operation without being constrained by the available time. The technical coefficients of KTBL indicate that with a fieldwork efficiency of 0.78 hectares per hour, associated with a single row, 0.75 meters, corn chopper implement, the farm agent can accomplish 23 hectares in 29.44 hours. Nevertheless, KTBL additionally indicates that the harvest and store of silage maize require three different partial works (*Teilarbeiten*): Fieldwork operations, transport, and stocking. In this current model version, only the first partial work was considered (fieldwork); therefore, an underestimation of the actual time of the full harvesting operation is still present. For harvesting operations for other crops, KTBL provides a single partial work (fieldwork: e.g., Combine harvesting of wheat, rye, triticale, with a standing wagon at the field edge and straw deposit in swath) and no underestimation arises.

Crop rotations

In the context of the research project "Regional Climate Change" (DFG - *Forschergruppe 1695 Regionaler Klimawandel*) funded by the German Research Foundation, a survey was conducted in 2013 with the objective to capture relevant land-use and farm-level information on the research region of the Central Swabian Jura in Southwest Germany. Based on this information, crop rotation dynamics were distinguished and compared with the model simulation outcomes. Typical crop rotations in the research area correspond to four-year crop rotations. Table 3.11 shows common and observed crop rotations in the research area. Figures 3.25, 3.26 (correspondig to the baseline scenario), 3.27 and 3.28 (corresponding to the scenario with high maize allowance and "long" rapeseed after

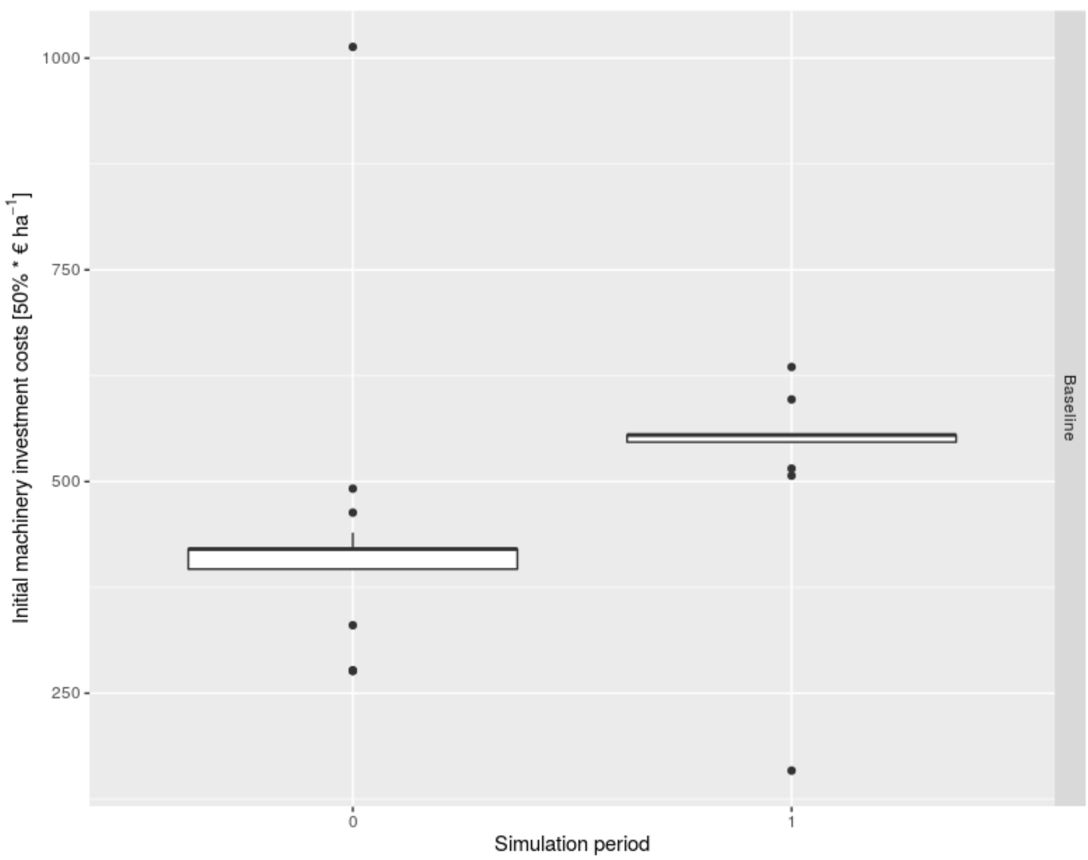

Figure 3.24: *Total investment cost of optimal machinery portfolio (50 percent of initial investment cost, no replacements). Results presented over 50 design points of the uncertainty runs (Sobol's sequence) for the first (0) and second (1) simulation periods. Results showed for baseline scenario.*

Year 1	Year 2	Year 3	Year 4	Year 5
W. Wheat	S. Barley	W. Barley	W. Rape	-
W. Wheat	W. Wheat	W. Barley	W. Rape	-
W. Wheat	W. Barley	W. Rape	-	-
W. Wheat	S. Barley	W. Rape	-	-
W. Wheat	S. Barley	W. Barley	S. Maize	-
W. Wheat	S. Barley	W. Barley	Oats	W. Rape
W. Wheat	S. Barley	S. Maize	-	-
W. Rape	W. Wheat	W. Wheat	S. Barley	-
W. Rape	W. Wheat	S. Barley	W. Barley	-

Table 3.11: *Typical crop rotation dynamics in Central Swabian Jura. Source: Survey to farmers in context of DFG Regional Climate Change Project.*

wheat required gap) show the long-term simulated crop rotations with the model version here discussed.

The resulting crop rotation courses from the baseline long term simulations show that winter rapeseed is grown mostly after winter barley, and to a lesser extent after spring barley and fallow area (Figure 3.25). Likewise, winter wheat is mostly produced on plots where rapeseed was grown in the previous year; also, silage maize serves importantly as a preceding crop for winter wheat production (Figure 3.26). In the baseline scenario, it is not possible to grow winter rapeseed after winter wheat due to the tight time window between the harvest of the latter and the sowing of the former crop. For the scenario results with climate change effect, high maize sells allowance and "long" rapeseed after wheat required day-gap, it is possible to observe the dynamics of rotation that arise from the assumed and implemented climate change effects (Figures 3.27 and 3.28). It is relevant to notice that the simulations show a result in which winter rapeseed is grown to a significant extent after winter barley, winter wheat, and at some simulation periods, after fallow (Figure 3.27). It is important to point out that the crop rotation results from figures 3.27 and 3.28 correspond to not-yet observed and assumed climatic situations and that result from the dynamics captured in the MPMAS model. It is also relevant to point out that the model configuration that is here discussed does not yet contain all the cropping possibilities that real farmers have in the Central Swabian Jura (e.g., triticale, rye, oat, sugarbeet, potatoes, field grass are alternative crop production possibilities that are not yet included in the model system).

3.3.3 Economies of size in farm mechanization

Costs

The validation of the cost results from the optimization runs was made in relation to the estimates provided by KTBL (2020). According to KTBL (KTBL, 2020), variable costs

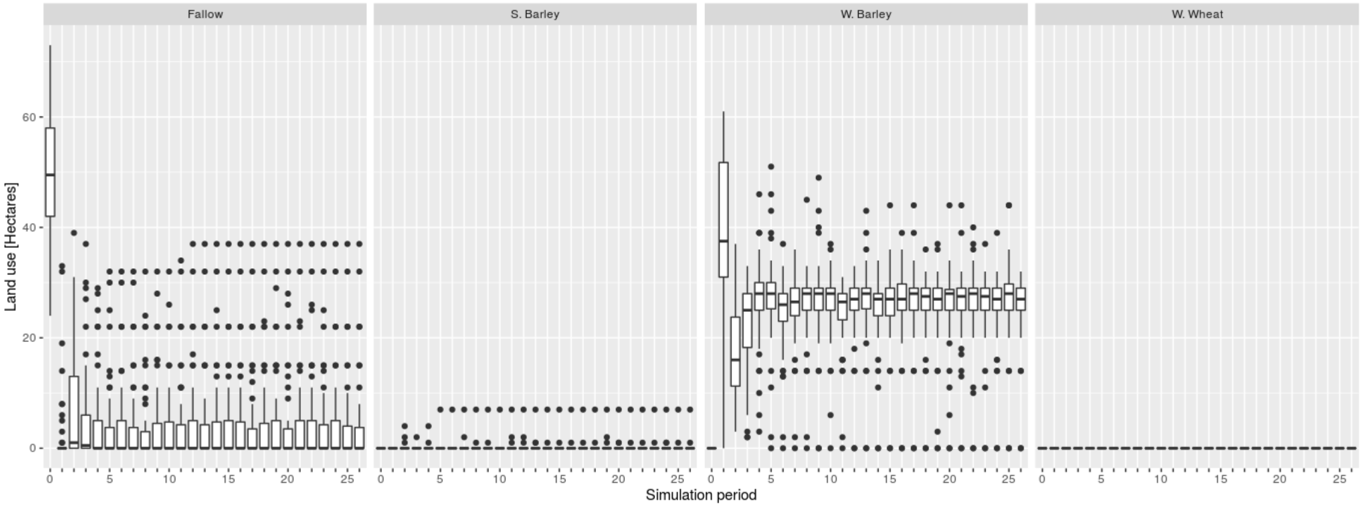

Figure 3.25: *Area of winter rapeseed after fallow, spring barley, winter barley and winter wheat. Results from long term simulations. Baseline scenario.*

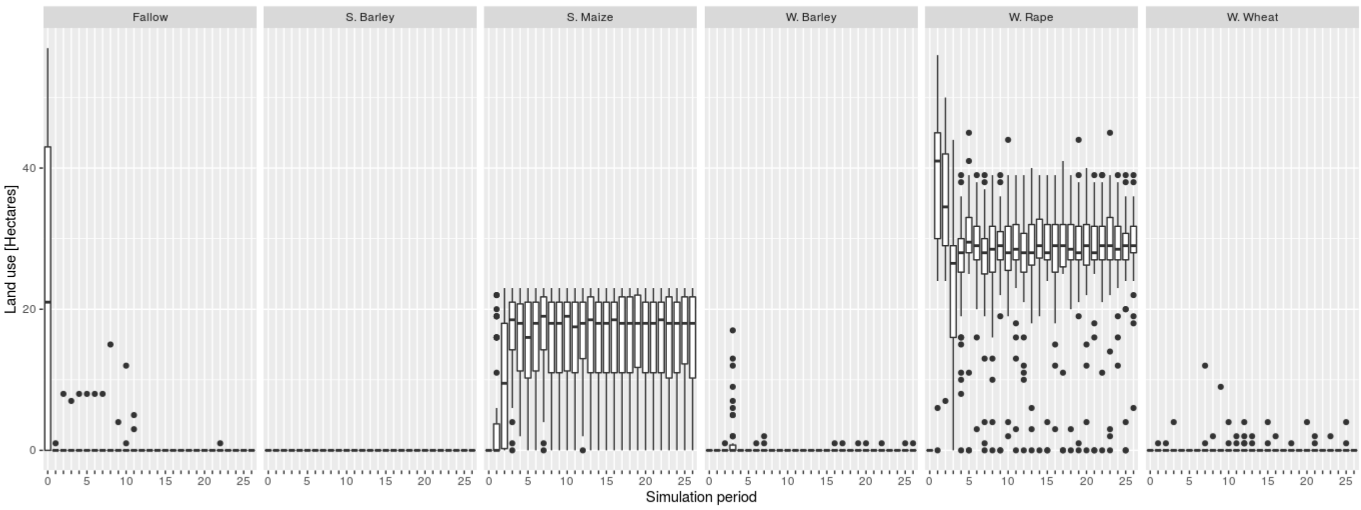

Figure 3.26: *Area of winter wheat after fallow, spring barley, maize, winter barley, winter rape and winter wheat. Results from long term simulations. Baseline scenario.*

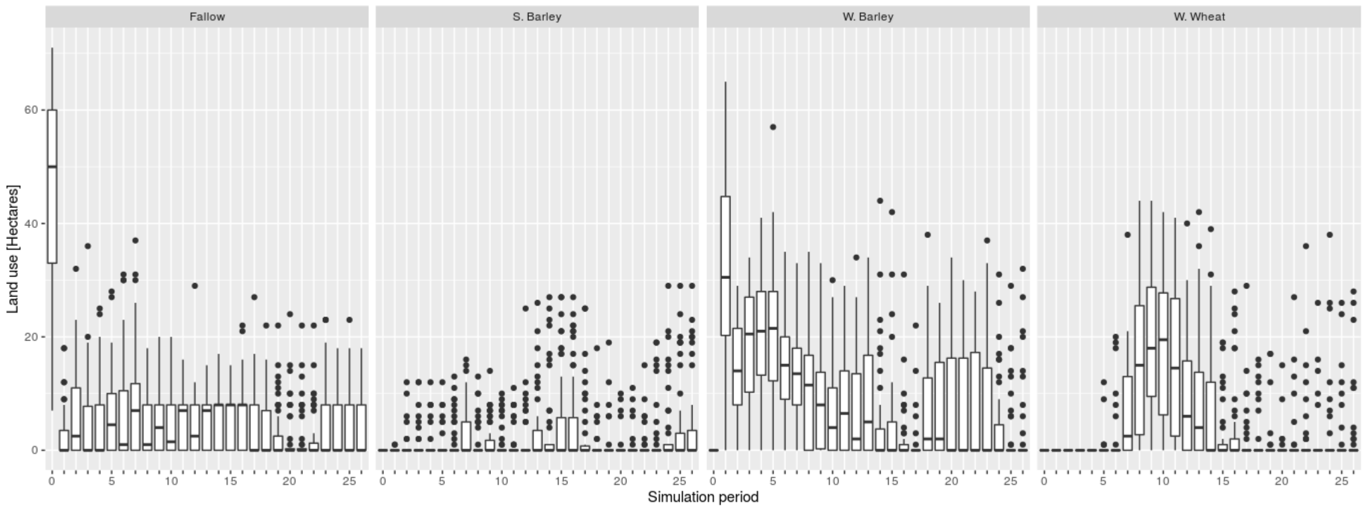

Figure 3.27: *Area of winter rapeseed after fallow, spring barley, winter barley and winter wheat. Results from long term simulations. Maize scenario - "long" rapeseed after wheat required gap.*

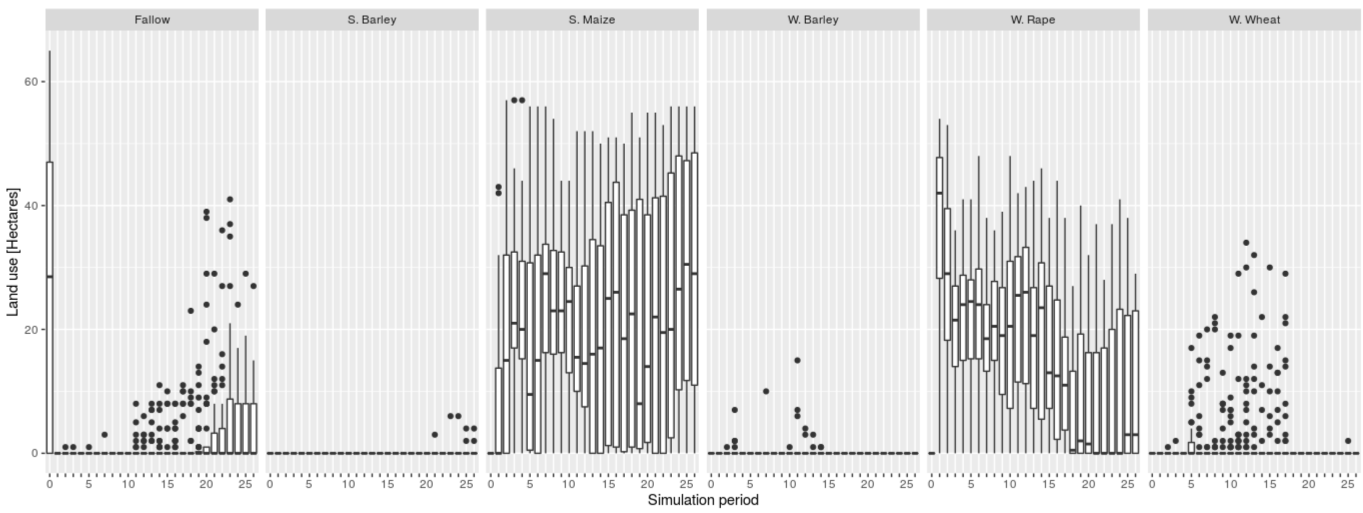

Figure 3.28: *Area of winter wheat after fallow, spring barley, maize, winter barley, winter rape and winter wheat. Results from long term simulations. Maize scenario -"long" rapeseed after wheat required gap.*

Crop	Mechanization level (kW)	Variable cost (€/ha)	Fixed cost (€/ha)
Winter Wheat	102	876.59	302.00
Winter Wheat	200	886.55	322.00
Winter Rapeseed	102	830.47	200.25
Winter Rapeseed	200	840.29	226.78
Winter Barley	102	726.55	288.80
Winter Barley	200	735.33	308.14

Table 3.12: *Compilation of variable and fixed costs for two different mechanization levels. KTBL 2020 - Compiled from the online applications.*

Mechanization level (kW)	Weighted variable cost (€/ha)	Weighted fixed cost (€/ha)
102	803.09	263.41
200	812.51	285.35

Table 3.13: *Weighted average of the variable and fixed cost based on a 0.333 share of the full costs of each crop. Example for variable cost with mechanization level 102:* $0.333 * 876.56 + 0.333 * 830.47 + 0.333 * 726.55 = 803.9$. Based on online applications of KTBL (2020).

contain all direct costs (direct inputs such as seed, kalk, fertilizer), variable machinery costs (*Variable Maschinenkosten*, i.e., Diesel), services paid, interest paid, and labor costs (*Lohnkosten*, i.e., wages). The calculation of variable costs in the optimization model was made in terms of direct costs (direct inputs such as seed, kalk, fertilizer), expenditure on fuel requirements, payment of wage for hired labor, and services on hired fieldwork operations (harvesting as long as it was an optimal decision). Furthermore, the optimization model's fixed machinery costs were calculated as the sum of payments for depreciation (linear method) of the equipment and machinery as well as machinery fees payments.

Figures 3.29 and 3.30 show results for variable and fixed costs resulting from the optimization runs. It is possible to observe that, for the case of variable costs (Figure 3.29), the optimization results show a median payment per hectare that ranges from 725 and 840 Euros per hectare across all the evaluated farm sizes. Likewise, the resulting fixed costs (Figure 3.30) show the expected degression as the evaluated farm sizes increase, and the median payments per hectare range between 650 and 170 euros. It is worth noticing that the majority of the farm sizes evaluated (i.e., from 150 to 630 hectares) depict median fixed costs ranging from 300 and 170 Euros per hectare. These values for optimal payments of variable and fixed costs are in accordance with the estimations provided by KTBL (Tables 3.12 and 3.13). Even when these calculations that KTBL provides refer to pre-calculations of reference values of suggested production and fieldwork processes, they are a good indicator for comparison purposes with the optimization results. Given that a full uncertainty analysis and a comprehensive representation of the farm structure and relationships are considered in the optimization model, the model results are able to deliver good predictions of expected and optimal machinery investments (and the derived, relevant cost courses) across the evaluated farm sizes.

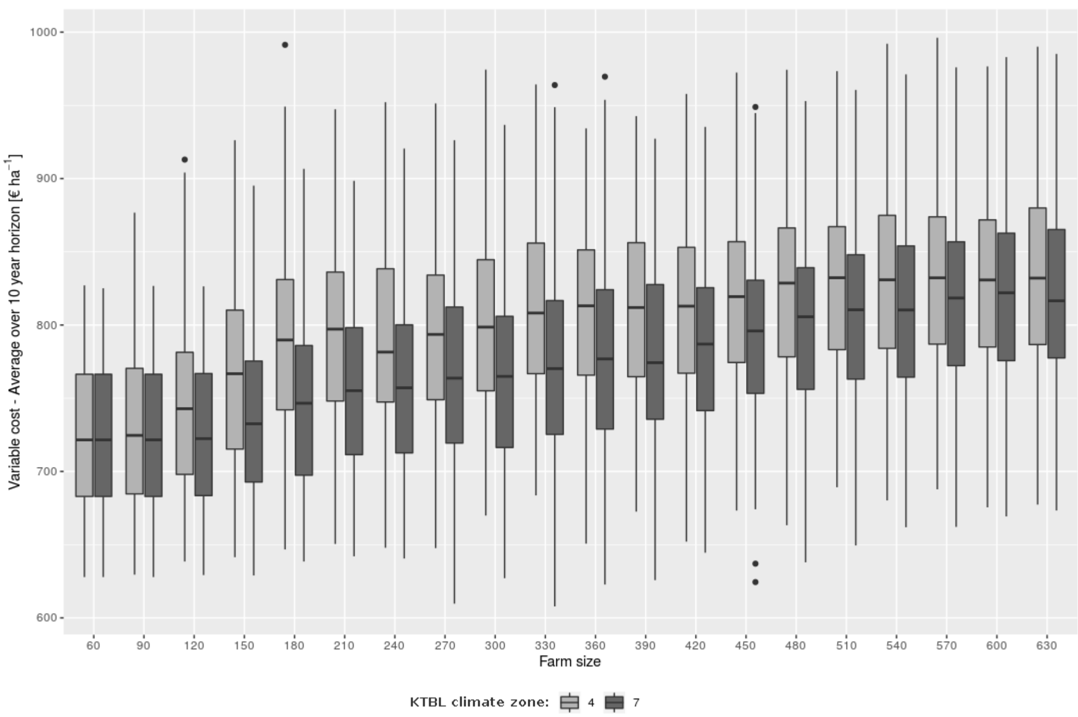

Figure 3.29: *Total variable costs from optimization results (average over whole planning horizon of 10 yeas). Results presented over 150 design points of the uncertainty runs (Sobol's sequence).*

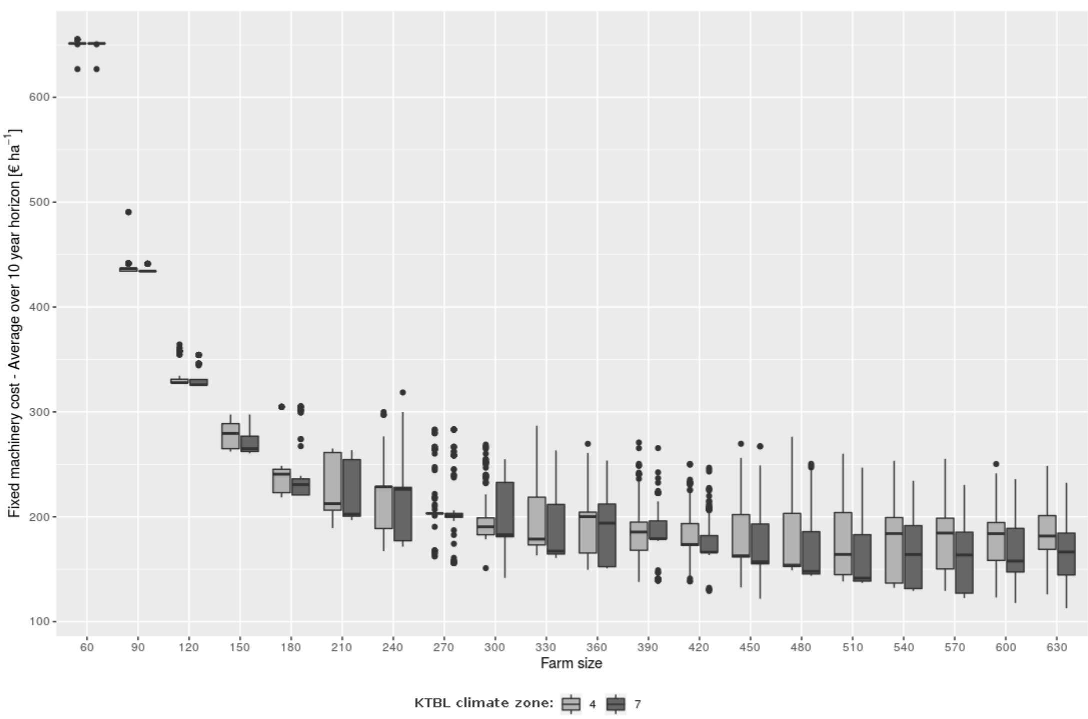

Figure 3.30: *Total fixed costs from optimization results (average over whole planning horizon of 10 yeas). Results presented over 150 design points of the uncertainty runs (Sobol's sequence).*

Machinery portfolio cost

The estimations on the optimal machinery portfolio's total investment cost from the optimization runs can be observed in figure 3.31. For this figure, the 50 percent of the investment cost (from the initial acquisition of the overall optimal machinery portfolio - without replacements) was calculated and is presented. The reason for this calculation is that the accounting values provided by the public institutions presented above correspond to acquired assets to which a certain age is unknown. Considering that the book value is equal to the investment cost minus the accumulated depreciation, the expected value from the optimized investment portfolio is estimated in the model results by accounting an average accumulated depreciation of 50 percent of the total initial investment cost.

By comparing the estimation provided by the public offices and the results from the optimization runs, it can be observed that the yielding investment costs in the machinery portfolio is comparable to what is observed in real-world farms and test farms; the total expected investment costs resulting from the optimizations range between 1,500 and 800 Euros per hectare (for the range of farm sizes between 150-630 ha); the estimations provided by the public offices are contained in the ranges of these optimization results.

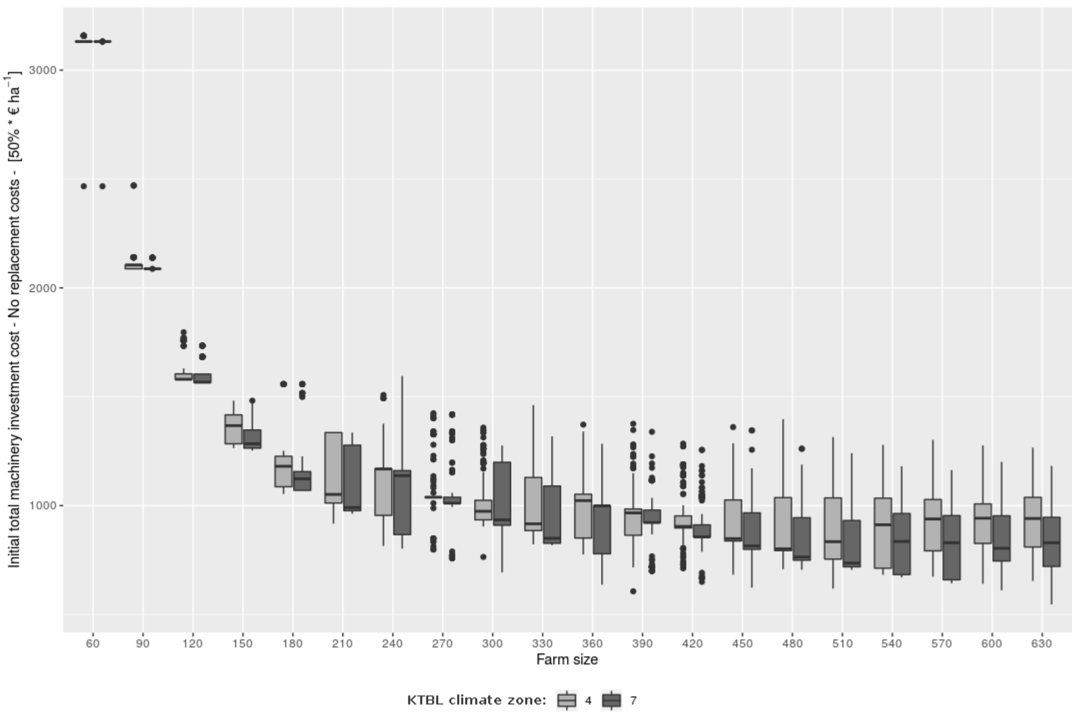

Figure 3.31: *Total investment cost of optimal machinery portfolio (50 percent of initial investment cost, no replacements). Results presented over 150 design points of the uncertainty runs (Sobol's sequence).*

Chapter 4

Enhancing the MPMAS modeling framework

Contents

4.1 Farm machinery associations for dealing with indivisibilities in machinery acquisition

4.1.1 Introduction

In agricultural regions where a small farm structure predominates, as in Southwest Germany (Happe et al., 2008), the acquisition of lumpy technologies such as farm equipment and machinery typically leads to situations where the technology is not fully utilized. In light of these eventualities, farmers often use alternatives to acquire adequate machinery and equipment capacities by engaging in indirect interactions such as those represented by rental or hiring markets. Similarly, farmers also engage in more direct ways of interaction in the endeavor of establishing the best managing plan for machinery capacity acquisition. More direct ways of farmer-to-farmer interaction are, for example, those that derive from the establishment of cooperation agreements in the form of either machinery rings or farm machinery associations. These cooperation agreements have the objective of keeping and enhancing competitiveness at the farm level by reducing costs through the achievement of degression effects in the use of labor and capital (e.g., equipment) and improved farm machinery management (Doluschitz et al., 2011).

This subchapter is inspired and motivated by examining the type of cooperation arrangement described in the inquiry of Aurbacher et al. (2011); this arrangement takes the form of a farmers' machinery association between five farmers in Southwest Germany. In their investigation, Aurbacher et al. (2011) study potential economic reasons that lead to a failed establishment of the farm machinery association. In the context of this Ph.D. thesis, an external module for the agent-based modeling software MPMAS is constructed and implemented. The external module consists of a theory-based algorithm that communicates with the agent-decision module of MPMAS. The external module simulates group formations for achieving joined investments in lumpy technologies such as agricultural equipment and by acquiring shares of the investment cost and capacity use.

What is the added value of designing and implementing a machinery-sharing interaction module in MPMAS? Designingn and implementing an external interaction module for shared investments in farm machinery serves as an appropriate step towards an improved representation of the acquisition of work capacities derived from indivisible technologies; a farm decision model representing farm machinery decisions should ideally consider all the relevant alternatives for acquiring the proper machinery capacities. In the MPMAS modeling framework, joint investments in assets are not captured, yet, in reality, shared investments in farm equipment represent an essential practice among farmers. The programming of a theory-based external module for MPMAS aims to contribute in this endeavor.

The objectives of this subchapter are to present the functioning and the potential of the external MPMAS module for joint machinery acquisition in farm machinery associations/groups. The subchapter also aims to explore, with a simplified use-case and under the theoretical principles of i) complementarity for shared investments, ii) homophily, and iii) preferences for small groups, different scenarios where autonomous simulated farm agents establish machinery association groups while considering a flexible representation of the relevant, complex and interconnected relationships between the various potential activities and available resources on the farm in a MIP farm-level model (e.g., labor and machinery scheduling, financial profitability).

4.1.2 Group composition and participation on machinery sharing arrangements

Artz et al. (2010) establish a conceptual framework for organizing and understanding the nature of cooperative arrangements in input sharing (e.g., typically machinery and equipment). The authors explain that the participation in institutional arrangements that allow the inter-farm use of technology puts farmers in a trade-off between the access to economies of scale (internal and external) on the one hand and incurring in transaction costs, on the other hand. The economies of scale arise from the increase in the number of hectares serviced by the shared machinery or equipment while reducing average production costs and from the advantages that larger farms can have acquiring inputs at lower costs (de Toro and Hansson, 2004). Yet, putting a farmers' association group in functioning can also trigger transaction costs in the form of timeliness (i.e., yield reduction due to late fieldwork operations, in particular, seeding operations), monitoring costs, and costs arising from collective decision making (Artz et al., 2010; de Toro and Hansson, 2004; Larsen, 2007; Hansmann, 1996).

The explanations on the extent to which one individual decides to work with another one go beyond the traditional object of study of economics. The search for theoretical approaches requires exploring other fields of study, namely, the ones of the network theory, psychology, and group composition. Numerous studies from these fields of study suggest that two of the most relevant factors that increase the desire of individuals to engage in interactions with others and incentive working together with them are the existence of similarities (e.g., races, sex, status, closeness, friendship) and complementary competences (Burck, 2016; Carley, 1991; Lott and Lott, 1964; Lazarsfeld and Merton, 1954; Thibaut and Kelley, 1959).

In their contribution, Hinds et al. (2000) provide a theoretical discussion about how people often choose workgroup members to achieve successful functioning. The authors explore individual attributes, relational attributes, and previous structural ties as determinants of work partner choice and indicate that the factors that modify the confidence of individuals in the ability of others to contribute successfully to a group point towards homophily (i.e., individuals prefer to work with others who are similar to themselves) and complementarity (i.e., individuals look for complementary partners that have skills or abilities that they do not possess).

Given the potential benefits that, at least in theory, farmers can achieve from investing and using shared equipment, one could expect that farmers make extensive use of this practice. Nevertheless, as Aurbacher et al. (2011) point out, such cooperative arrangements are not widespread in Germany. The authors identify three main reasons why this might happen in reality; first, unfavorable selling prices for used machinery can hinder one farmer's incentives to join other farmers into a cooperative arrangement. Secondly, farmers usually replace their old machinery and equipment at different times, and this also can hinder their incentives to enter into cooperation with other farmers if there are no synchronic replacements. And finally, the distribution of the costs plays a role in shaping the incentives of farmers to enter into cooperation; the establishment of a uniform price at the level of the lowest willingness to pay can potentially stop an association from being established because payments of the total costs might not be covered. However, and despite not being a (scientifically documented) widespread practice among farmers in Germany, anecdotal references indicate that the establishment of private machinery sharing associations/groups is a reality among farmers to maintain competitiveness and rentability to changing economic conditions (Kremer-Schillings, 2017).

For the U.S. case, a detailed description of machinery sharing arrangments in the form of farmers association groups was provided by Artz et al. (2014). The authors conducted case studies of farmers to obtain an in-depth understanding of the dynamics of shared investments and machinery use and demonstrate the different organizational alternatives that farmers establish to share machinery and equipment. From the documented experiences, the authors concluded that scheduling efficiency can help save on transportation costs and allow for the sharing of time sensitive equipment use. From their analysis of the study cases, adequate and in-advance planning of the use of time sensitive equipment was a common practice that helped to overcome the challenges of machinery use scheduling.

Additionally, Artz et al. (2014) documented that farmers identified the group's size as a relevant factor for defining a farmers association group. The documented experiences of farmers indicated that having fewer people sharing gives farmers more flexibility when they can get the machine and that the association would not work as efficiently with more people or larger farms. The authors further emphasize that similarities and complementarities of the farms and people involved are fundamental when looking for potential partners for a sharing arrangement.

In another study for the U.S., Artz et al. (2010) conclude from their examination of 10 cases of machinery sharing groups in the Midwestern U.S., that farmers typically develop a variety of methods in order to deal with challenging aspects of group-sharing, such as the scheduling of equipment and machinery use. For example, the authors provide evidence that shows that farmers routinely establish written agreements to manage the use of large and frequently required machinery such as combine harvesters.

Furthermore, for a production cooperation project of six part-time arable farmers in Sweden, de Toro, and Hansson (2004) quantify the effects of cooperation in terms of machinery costs (with consideration of timeliness), investment demands, the time required for fieldwork, and social features of the association. The authors estimate that sharing arrangements for machinery investments and use allowed farms to reduce total costs by around 15 percent and investment requirements by 50 percent. The authors pointed out that challenging weather conditions were a determinant cause of timeliness costs even with large machinery that provides high field capacity.

4.1.3 Design principles for a farmer association module for multi-agent systems

Parker et al. (2003) and Berger and Troost (2012) examine the key components of Multi-Agent Systems for Land-Use/Cover Change. In their reviews of the multi-agent system modeling approach, the authors identify that the component that simulates human decision-making is a crucial element towards developing a multi-agent system modeling approach. The simulation of human decision-making for defining a multi-agent system approach is characterized by autonomy and communication. On the one hand, the agents that make choices, e.g., on land use or investments, should be consistent on their actions and should be driven by a specific goal, and, on the other hand, the choices of one agent can have the potential to affect the choices of other agents through a unifying environment or mechanism (Parker et al., 2003).

As a golden rule, specifying a module that simulates the formation of farmers' association groups in machinery and equipment sharing must be coherent with the assumed agent's objective defined as a constrained optimization in the form of a mixed-integer programming problem in MPMAS. In this implementation, farm agents autonomously and independently select farm plans to optimize an objective function that requires maximizing cash withdrawals at the end of a planning period. In this sense, preserving the autonomous decision making of the farm agent is a design principle.

4.1.4 Modeling shared investments in farm machinery and equipment: Pre-considerations

Unlike for machinery rings, accurate documentation regarding the dynamics of the functioning and consolidation process of farmers' association groups for shared machinery investments in Germany is hard to obtain. The nature of this type of association is more informal and requires that the members of the machinery association voluntarily and openly express their experiences about their particular cooperation arrangement. Usually, this is only possible by establishing a direct personal relationship with the farm members given that much of the dynamics that govern the establishment of farmers' cooperation groups depend on personal characteristics (e.g., a good relationship between one colleague farmer or not, familial relationships, among others).

To the author's best knowledge, peer-reviewed articles that address the topic of empirical incentives, drivers, and functioning of farmers' association groups for machinery sharing are limited for Germany. For instance, Aurbacher et al. (2011) offer potential explanations as to why farmers might be reluctant to establish farmers' association groups in machinery sharing despite the potential benefits in the form of economies of scale that can be acquired. The authors show that path dependency plays an important function, and it may restrain farmers from building cooperative arrangements in Southwest Germany. Another study for Germany is the one of Feil et al. (2015), the authors employ discrete choice experiments to analyze farmers' preferences for founding cooperative arrangements while considering non-monetary factors in the functioning of the groups' cooperation arrangement. Their results suggest that similar ages between farmers, higher expected increased profits, long years of knowing a potential collaborator, and similarities in the production activities between collaborators (e.g., if both practice animal husbandry together with arable farming) are factors that positively encourage farmers to establish cooperative arrangements.

From the reviewed documents and experiences that show the workings of farmers association groups, it became soon clear that these types of cooperation arrangments can take numerous forms. The various arrangements cover informal kinds of verbal agreements or written contracts and business entities, these, with established and negotiated rules of capacity use and investment contributions on the one hand. Moreover, the taxonomy of potential cooperative arrangements does not solely include one factor of production; farmers can share pieces of equipment with or without labor sharing capacity, equipment sets, or equipment sets and labor. The extensive constellation of arrangements calls for the necessity of identifying the underlying structural characteristics of farmers association groups' functioning if one wishes to construct a model for interaction among autonomous decision-makers. Therefore, the approach here followed focuses on representing relevant structural dynamics to define cooperation between two or more independent decision-makers. These structural dynamics are discussed below.

For the conceptualization and implementation of a generic, theory-based, algorithm that serves as an external module for MPMAS, the author is based on the observation that " [...] *although preferences for working with others may evolve over time, there* *is often a point at which a person must make an explicit choice*" (Carley, 1991). The focus of the implementation of an external interaction module in MPMAS is placed on this specific point in time. It is further assumed that once farm agents have decided to enter in cooperation with other farm agents (and an association group is effectively constructed), the decision is binding, and the cooperation group will exist as long as the lifetime of the shared equipment allows a shared capacity provision.

The problem that the external MPMAS module should ideally solve in this context is: *Given that a farm agent – in consideration of its optimality conditions, farm-level resource relationships, and endowments – autonomously decides to acquire a piece of machinery or equipment "m" with a share "s" (that provides the corresponding capacity and requires the corresponding investment cost), with whom should it aim to enter into cooperation?*". The following described principles are derived and further abstracted from the documented experiences of farmers machinery associations, and represent the structural boundaries and assumptions on which the external MPMAS module for shared investments and cooperation are grounded on:

1. Farm agents that are candidates for the establishment of a cooperation group will qualify as such as long as the potential established group fulfills a complementary precondition for the upfront payment of the desired piece of equipment.

2. A farm agent that can potentially participate in more than one sharing group for one piece of equipment (as a result of the fulfillment of the complementarity principle) should take part in the group that has fewer members. Furthermore, it will participate in a sharing group where an average measure for distance among all the group members is the smallest. The algorithm's implementation allows that the measure for distance is left open for the adequacy of any implementation as long as it orders groups with different degrees of closeness (e.g., physical closeness, friendship indexes among potential group members).

4.1.5 Technical implementation of interaction algorithm

The algorithm that rules the formation of farm agents' interactions for the shared investments in machinery and equipment runs as an external module of the Mpmasql4 software infrastructure. The preconditioning step for the implementation of the agents' interaction module is the existence of a recursive-dynamic model (ideally with intertemporal planning). The application presented in this subchapter was built by expanding the recursive-dynamic model described in subsection 6.1 of chapter six of the documentation in this thesis, and that was also used for the subchapter 3.1: "Dynamic effects of shifts in fieldwork time on land-use and machinery acquisition." The model was extended for capturing the communication with a Python (v.3.6.5) program, where the matching algorithm of farm agents into sharing groups is contained.

In a typical recursive-dynamic simulation, decision-makers (independent farm agents) establish optimal multi-year plans ($t = 1, 2, 3, ..., T$). These optimal multi-year plans are periodically updated; after a specific period has passed (e.g., typically, one agricultural season), the agents will evaluate the past decisions' outcomes. Based on this evaluation, the agents revise and update their optimal multi-year plan. At the beginning of the first simulation, all farm agents establish a T-year plan, deciding, for example, on optimal land use, amount and type of machinery to buy, labor units to hire or fieldwork activities to perform for all the years in the T-year plan. The farm planning is based on expectations on future costs, revenues and additional constraints (e.g., crop rotations, financial constraints). Once the agents decided on their first long-term plan, they implement only the first year, and this represents a binding decision. The planned crops will be sown and managed, the investments they had planned will be realized, and the hiring of labor will be performed in the year one. Once the period has passed, the agents can perform a second long-term decision based on the outcomes of their previously implemented farm plan, this is stage corresponds to the second simulation. The point in time where next long-term farm planning decision occurs is conceptually located directly before the harvest of the crops. [1]

The reason of conceptually locating the whole-farm decision process before the harvest of the crops is that a revision of the long-term farm plan requires updated information and no surprises: At this point, it is assumed that the farm agents should know the actual yield of the standing crop (e.g., due to climatic reasons the expected yield and the actual yield might be different). Also, the actual prices for which the yield can be sold are assumed to be observed, and all other prices of inputs and assets for the immediate upcoming period are assummed to be known (whereas the future yields and prices of periods beyond the upcoming one are still unknown, and the farm planning is based again on expectations).

For the use of the interaction algorithm, the decision point described above is modified by adding additional decision stages before a farm agent implements its immediate plan. At the moment in which the farm agent establishes (correspondingly, revises) its long-term farm plan, the decisions for the immediate upcoming year are not directly implemented, but rather understood as a preliminary decision. The preliminary decision has the purpose of establishing the initial conditions for communication between the autonomous decision of one farm agent with the other farm agents from the agent population. When considering interactions, the (optimal) farm plan of a farm agent might include the choice of decision variables that can only be effectively implemented as long as other farm agents establish their farm plans in a particular way. For example, the decision of a farm agent to grow a specific crop might depend on the capacity to sell this crop's yield through a farmers' cooperative, but the farmers' cooperative might be willing to receive the yield as long as it has the warehouse capacity, and this capacity may depend on the production levels of other farm agents, and the rights they have on selling to the farmers' cooperative.

In this application, a farm agent might decide that it is an optimal decision to invest, for example, in one tractor of 200 kW with a 50 percent share of the investment costs and corresponding 50 percent of capacity provision: The extent to which this farm agent can acquire this investment depends on the decision of other farmers also interested in acquiring the remaining shares of the tractor, e.g., five additional agents, each interested in acquiring a 10 percent share the investment costs and corresponding capacity provision, or two additional agents, each interested in acquiring 25 percent, or one additional agent interested in a 50 percent share of the same tractor. In this sense, the preliminary decision made by each farm agent is not strictly speaking an investment decision (it is

[1] In the model used in this subchapter, a more detailed representation of selling and harvesting timings is considered. See the documentation section of this thesis, chapter six, subsection 6.1., for a full description of the submodel component MPMAS of the model system MPMAS_XN.

not implemented), but it is rather understood as an application for a shared investment on a specific machinery or equipment specification. If no other farm agent or group of agents establish a complementary investment application on the same machinery or equipment, then the farm agent in consideration would need to revise its farm planning without the possibility to apply again to a shared investment (so far, only one preliminary decision is considered) leaving the only alternative of acquiring the desired equipment in a full share (i.e., individual investment in the full unit of the technology).

The external script is specified in the configuration files of MPMAS tool Mpmasql4 and is called right after the preliminary decision is taking in order to simulate interactions. The information required by the interaction algorithm for the definition of an association is i) the machinery or equipment type and ii) the share of the investment cost (and corresponding capacity provision) in which each agent desires to invest. Once the agent has applied for its desired investment format in the preliminary decision, the interaction algorithm performs the following actions:

1. The Python interaction module reads the MPMAS output files (preliminary decision) and saves in memory all the identifiers of farm agents that apply for an investment of one unit of machinery "m" with a specific share "s", and proceeds by constructing all potential groups of farm agents that have complementary investment shares (farm agents whose investment shares add up to 100 percent, or the full acquisition cost and capacity of the machinery).

2. The Python interaction module prints out the potential farm agents' association groups attending the complementarity principle described in point 1. In a second step, the algorithm organizes all the potential farmers' groups based on their members' quantity (i.e., group size) in ascending order. The ordering has the purpose of identifying the farm agents' association group that will be conformed first, based on the design principle that states that smaller groups are always preferred against larger groups of farm agents. For example, the autonomous investment applications of four farm agents could result in a situation where three potential groups are valid: One group could be formed by the two agents A and B, each having a 50 percent share, another group could be formed by agent A, C, and D, where C and D both have a 25 percent share, or a third group with B, C, and D. The interaction algorithm would, in this example, conclude that the group of farm agents A and B is the one effectively established. The interaction algorithm additionally recognizes the cases where multiple farm agent association groups hold the same number of farm agents (e.g., several groups with "n" farm agents). In such situations, the algorithm in the Python's module is designed so that the average distance from every farm agent to all other farm agents members of the same group is calculated to enter in a tie-breaking mechanism. The consideration of distance is understood in the broad sense and consists of a measure to locate farm agents in a landscape. The group of farm agents with the smallest average distance among its members is the group that is first established. Still, in the unlikely cases where the average distance from every farm agent to all other farm agents members of one group is the same to the average distance of the members of a second group, the interaction algorithm includes a second tie-breaking mechanism. The second tie-breaking mechanism consists of a deterministic calculation of an index based on household's age characteristics; the purpose of the generated index is to produce a measure con-

sisting of several decimal points for its comparison among conflicting groups. The index is produced for each farm agent in each of the tied groups. It is calculated as the average age of the two oldest household members and divided by the age of the youngest household member; the resulting value is consecutively multiplied by the size of the household. By comparing the resulting average group index to another one, the tie can be broken, and a farm agents' association group can be determined.

3. Right after the first farm agents' association group is established, the interaction algorithm updates the file that contains the ordered collection of all potential groups for shared equipment. In this updating process, the interaction algorithm erases the first established group and all the other groups that contain farm agents' identifiers of the first established group. The reason is that once a first farm agents' association group is formed, the farmers that take part in this group no longer require to take part in any other groups in order to build complementarity with other agents. Once their group is formed, they can exit the process of group formation. All the remaining groups that depended on the exiting farmer(s) for building complementarity can no longer achieve it and, therefore, their potential group is dissolved.

4. The remaining groups of farm agents that can still achieve complementarity in their investment applications form a second round of decisions for the interaction algorithm. The above-described process of selection of a farm agents' association group is repeated exactly in the same way until no additional potential groups remain for formation.

4.1.6 Implementation in Mpmasql4 model

The external module for machinery sharing interaction communicates with the recursive dynamic, whole-farm multiperiod simulation Central Swabian Jura model written in Mpmasql4, described in subsection 6.1 in the documentation of this thesis and used in section 3.1 of this Ph.D. thesis. For proper communication between the Mpmasql4 model and the external module for machinery sharing interaction, several extensions of the model were, nevertheless, necessary.

The implementation of adaptations in the whole-farm multiperiod simulation model required three general elements of change:

1. Besides the usual machinery and equipment investment activities (for individual ownership of a full capacity of the lumpy technology), agents are now able to apply for the investment on a piece of equipment with a user-specified share (e.g., 20, 25, 50, 75 percent of the full cost and capacity provision of the equipment).

2. Each cropping activity that is optimally selected within the agent decision module (MIP) defines a specific set of fieldwork operations (e.g., sowing, plowing, harvesting) which can be fulfilled by employing fieldwork activities (i.e., the performance of a fieldwork operation with a certain equipment size and tractive power level). Fieldwork activities require a determined amount of time (hours) in accordance with the efficiency of the selected equipment employed.

The total amount of fieldwork with own machinery that is possible to perform in a half month, a corresponding weather level of the fieldwork operation, and soil resistance of the parcel, is restricted by the number of equipment or machinery units (and tractors) owned by the modeled agent and the number of days with suitable weather for the type of work to be performed. A fully owned combine harvester that can be utilized, for example, for 22 hours per day for 15 days, will allow an upper limit of 330 hours for the performance of fieldwork activities. With the introduction of shared investments in machinery, the shares apply to the capacity that the equipment provides; a farm agent with a 75 percent share of a combined harvester will derive 75 percent of the time capacity (247 hours) available to perform a harvesting fieldwork activity.

3. Farm agents that apply to a share of investment in machinery and aim for a complementing investment partner (or partners) consider paying the corresponding share of the technology's acquisition cost. The implementation is currently abstracted in the agent decision module for shared investments in Mpmasql4 and obviate the use of different forms of financing (credit plans with different credit limits and credit rates). It is currently assumed that farm agents that establish a farmers association group acquire the technology with an upfront payment, yet, the implementation can be easily adapted in accordance to the study case at hand. Moreover, the decisions to apply for the acquisition of a share of machinery and possibly enter into interaction with other agents can only be made at each simulation period (i.e., the effective decision point at the beginning of the agricultural season that is directly implemented by MPMAS). Under this implementation approach, farm agents are refrained with the possibility to plan the acquisition of a share of machinery in future planning periods within the given planning horizon. The reason of taking this approach is that it is unlikely to assume that in "t" periods in the future a farm agent will be able to find and establish a suitable working group for the purposes of running a farmer association group. Furthermore, this condition commits farm agents to evaluate their investment decisions regarding seeking a cooperation agreement even before the current equipment endowment arrives at its end of useful economic life. Given the long-run planning nature of a multiperiod programming model, farm agents will necessarily need to balance the economic effects of applying, investing and potentially obtaining a piece of shared equipment at the beginning of the first planning period while considering that they still might have a piece of equipment that has a residual life of "n" years and can still be economically used for those remaining years.

The adapted and extended Mpmasql4 implementation for communication with the external script recognizes that farms agent seeking acquisition of a share of particular equipment need to consider the corresponding share of investment cost (percentage of investment cost times the full cost of the equipment) in their financial balances of the pre-investment decision. The farm agent's decision to apply and invest in a share of equipment is realized while considering, on the one hand, the cost of the share of the desired equipment, and, on the other hand, the costs of all the other technologies that also demand liquidity as well as other factors requiring liquidity as part of the whole-farm planning. Nonetheless, capturing this adequate investment cost on the technology share is currently possible at the *pre-investment decision* (i.e., first decision stage). In the second and final decision stage (i.e., the effective implementation stage after the interaction outcome is provided by the external module), the financial balances do not yet capture the effective cost of the shares paid by the farm agents that successfully share a technology. In a nutshell: The farm agents acknowledge the cost of their share of technology in their whole-farm financial balance but without knowing that they will not need to effectively pay for it if a sharing group is eventually formed. Even when this observation does not affect the results of group formation dynamics for buying and sharing technology that will be shown in the use-case application, it is important to transparently communicate that the representation of the cost of the equipment share solely in the pre-investment decision overestimates the available liquidity that the farm agents have in the second and final decision stage. A potential technical solution involves an update of a specific function in the Mpmasql4 tool and it is discussed in the last section of this chapter.

4.1.7 Use case

To demonstrate the model system's functioning, the model is applied to a simple study case to simulate likely cooperation outcomes in machinery sharing with the adapted recursive-dynamic multiperiod model. The model is applied to simulate land use and investment decisions of five artificially created agents that differ structurally only in their farm sizes (60, 70, 80, 130, and 150 hectares). The farm agents can invest in full units of equipment and machinery (that provide full capacity and require that the full investment cost is born by each single farm agent) and can, additionally, apply for units of seeding equipment that provide shares of capacity and require the corresponding shares of the investment costs (20, 25, 50, 75 percent). For demonstration and exemplary purposes, it is currently considered that sharing of technologies can be done in the following seeding pieces of equipment:

1. Seeding machine, mechanical, attached, 2 meters, with a lifetime of 14 years and acquisition cost of 3,900 monetary units (*KTBL description: Sämaschine, mechanisch, angebaut, 2,0 m*).

2. Seeding machine, pneumatic, attached, 3 meters, with a lifetime of 12 years and acquisition cost of 16,000 monetary units (*KTBL description: Sämaschine, pneumatisch, angebaut, 3,0 m*).

3. Seeding machine, pneumatic, attached, 4 meters, with a lifetime of 12 years and acquisition cost of 20,000 monetary units (*KTBL description: Sämaschine, pneumatisch, angebaut, 4,0 m*)

4. Precision seeder - maize - 4 rows, with a lifetime of 8 years and acquisition cost of 15,000 monetary units (*KTBL description: Einzelkornsämaschine - Mais - 4-reihig*)

5. Precision seeder - maize - 8 rows, with a lifetime of 8 years and acquisition cost of 26,000 monetary units (*KTBL description: Einzelkornsämaschine - Mais - 8-reihig*)

The literature review informed the predefined investment shares, and these corresponded to typical shares of investments in equipment that are encountered among farmers in farm association groups. Moreover, it is important to notice that the specific user-specified shares restrict the maximum potential size of a farmer association group. A 20 percent investment share can only hold five farm agents under the complementarity principle introduced in the external module design.

In the same way as with owned pieces of equipment acquired in their full capacities and investment costs, it is considered, following German accounting practices, that machinery obtained with a shared contract is also depreciated to zero at the end of its useful economic lifetime (a full sunk cost). Currently re-selling of assets is not considered (it is assumed a non-existence of markets for used machinery given that this would require additional interaction modules in the modeling system). Machinery use beyond the economic lifetime provided by the equipment's specification is not possible in this model version.

Multiple scenarios were established to test and demonstrate the functioning of the model system for agent interactions. The scenarios control the residual life (i.e., remaining useful economic life in years) of endowed seeding equipment. The proposed scenarios were designed to influence the farm agents' incentives to acquire seeding equipment by directly controlling the equipment's remaining economic life; in this way, it is aimed to introduce distinctive behaviors in the incentives to acquire divisible shares of equipment' capacities if this is optimal according to the agents' decision module.

The scenarios were defined such that the two farm agents with the largest area of arable land (130 and 150 hectares) were endowed with a precision seeder for maize (4 rows) and a pneumatic seeding machine of 3 meters. The remainder of their machinery and equipment portfolio needs to be acquired through investments. The farm agents with smaller areas of arable land (60, 70, and 80 hectares) were not endowed with any equipment or machinery units, and they were expected to acquire their whole machinery portfolio also through investments. Furthermore, all the farm agents are endowed with 274,000 monetary units (approx. the minimum quantity of liquid capital required for the acquisition of a complete and necessary machinery portfolio) and 1,500 monetary units per hectare; in this way, and by design, larger farms have larger quantities of working capital.

Moreover, the residual lives of the endowed maize seeder (4 rows) and the pneumatic seeding machine (3 meters) are different across each scenario. The residual lives are varied between one and six years. Endowed equipment with higher residual life is, naturally, newer equipment. Likewise, a piece of equipment with a residual life of 1 year is an equipment that will be worn out after one more year of use and will not be longer available for economical use. The measures for homophily are based on distances between each farm agent to all the other ones, and these were assigned randomly for the exemplary runs, nevertheless, the external module allows flexibility in the introduction of more elaborated and complex measures of homophily or communication networks between farm agents.

The experiments were run for one simulation period (it is in this simulation period where the interaction takes place), a planning horizon of ten years, and two general yield trends; one where the yields are kept constant and one where the yields for cereals and rapeseed decreased five percent each year and silage maize yields increase five percent. An overview of the scenarios (and baselines) is provided in table 4.1.

Scenario	Residual life of seeding equipment (years)	Residual life applies to agents of
Residual00YieldConstant (baseline)	No endowment	60, 70, 80, 130, and 150 hectares
Residual01YieldConstant	1	130, 150 hectares
Residual02YieldConstant	2	130, 150 hectares
Residual03YieldConstant	3	130, 150 hectares
Residual04YieldConstant	4	130, 150 hectares
Residual05YieldConstant	5	130, 150 hectares
Residual06YieldConstant	6	130, 150 hectares
Residual00YieldEffect (baseline)	No endowment	60, 70, 80, 130, and 150 hectares
Residual01YieldEffect	1	130, 150 hectares
Residual02YieldEffect	2	130, 150 hectares
Residual03YieldEffect	3	130, 150 hectares
Residual04YieldEffect	4	130, 150 hectares
Residual05YieldEffect	5	130, 150 hectares
Residual05YieldEffect	6	130, 150 hectares

Table 4.1: *Scenario definition*

4.1.8 Use case results

Baseline scenarios: Land-use and demand for shares of seeding equipment

Figure 4.1 shows the optimal shares of investments on the seeding equipment resulting from the baseline simulations (no initial equipment endowments and two yield scenarios). The figure shows the pre-investment solution of MPMAS; this is the preliminary decision before MPMAS communicates with the external Python interaction module to accomplish the appropriate group formations. The figure shows that the largest farm agents (agents four and five with 130 and 150 hectares correspondingly) differ in their demands for shares of standard seeding equipment with respect to the rest of the farm agents. The two largest farm agents aim for a 25 percent share of a 3 meters seeding equipment, pneumatic and attached (*Sämaschine, pneumatisch, angebaut, 3,0 m*). Their decisions do not vary across the two baseline scenarios. The farm agents one and two (with correspondingly 60 and 70 hectares) would be willing to acquire a 25 percent share of a 2 meters seeding equipment, mechanical and attached (*Sämaschine, mechanisch, angebaut, 2,0 m*), and for the agent three (80 hectares) it would be optimal a 50 percent share of the same equipment.

With respect to the maize precision seeder equipment in the scenario with constant yields (i.e., no yield effect) in Figure 4.1, farm agents two to five would be willing to invest in a 20 percent share of a maize precision seeder of four rows. For the farm agent with 60 hectares, silage maize production is not an optimal decision at the constant yield level specified in the baseline scenario; therefore, only in the baseline scenario with positive yield effects for silage maize is possible to observe that the agent one (with 60 hectares) integrates the acquisition of a 20 percent share of a maize precision seeder of four rows into its optimal equipment portfolio. The non-acquisition of any maize seeding equipment is additionally reflected in Figure 4.2, where the effective and implemented land-use decisions are shown for all the here-considered farm agents and it can be observed that the farm agent one (60 hectares) does not engage in silage maize production unless a yield effect is introduced in the system.

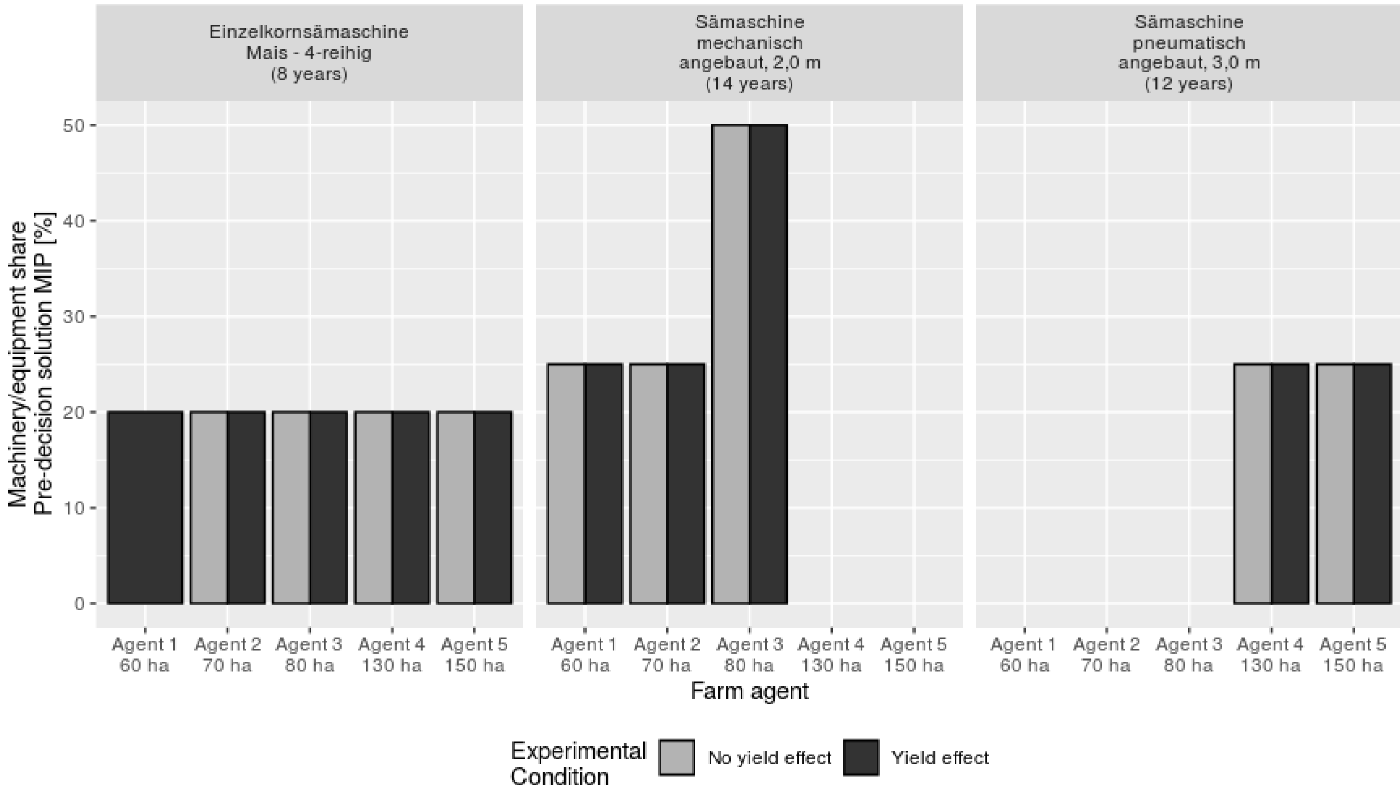

Figure 4.1: *Pre-decision results for the five evaluated farm agents: Demand for shared equipment. Baseline simulations: Residual00YieldConstant and Residual00YieldEffect.*

Effect of residual lifetime of seeding equipment on pre-investment decisions for shares of seeding equipment

Figure 4.3 shows the pre-investment decisions for the demand of shares of seeding equipment for all the farm agents (x-axis) across different scenarios that control the seeding equipment's residual years of lifetime (y-axis) endowed to the two largest farm agents (agents four and five). The results are shown in this figure for the scenario with no constant yield effect and equipment types with above-zero demand. The figure shows that farm agents four and five react as expected to the scenarios that control the residual lifetime of their endowed maize precision seeding equipment. When their endowed equipment is relatively new, i.e., has six or five years left in which it can be used (residual lifetime, y-axis), then these farm agents do not engage in seeking replacements for maize precision seeding equipment. The exercise results show that the closer the endowed equipment gets to obsolescence (i.e, less residual years of lifetime), it is more likely to expect that the farm agent will search for replacing their equipment and engage in efforts to acquire shared equipment.

The results in Figure 4.3 indicate that when farm agent four (with 130 hectares) experiences four years left in which it can economically use its endowed maize seeding equipment, it is appropriate to begin searching for a replacement in the form of a 20 percent share of a maize precision seeder of four rows (Einzelkornsämaschine - Mais - 4-reihig). The farm agent five (with 150 hectares) begins its search for a replacement when the residual lifetime of its endowed maize seeding equipment is three years.

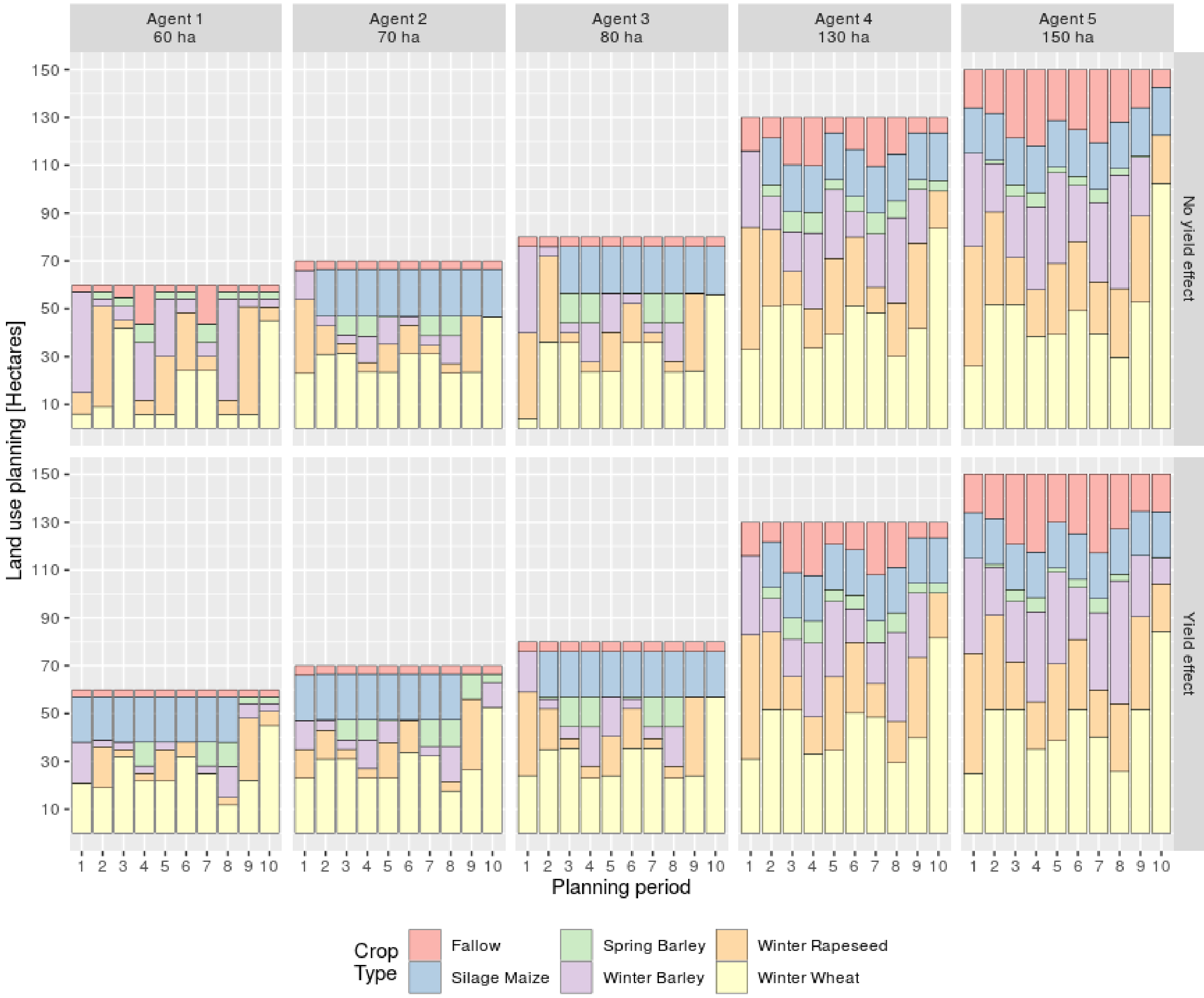

Figure 4.2: *Land use results for the five evaluated farm agents after interaction outcomes. Figure shown for baseline scenarios: Residual00YieldConstant and Residual00YieldEffect.*

Across the scenarios that control the lifetime of endowed machinery to agents four and five, it can further be observed in Figure 4.3 that for agents one, two, and three, it would always be an optimal decision to invest in one maize precision seeder of four rows. This result is expected since these farm agents (one, two, and three) do not have any seeding equipment endowment by definition in the experimental design.

The results are consistent if one attends Figure 4.4, where the pre-investment decisions for shares of seeding equipment units are shown for the scenarios with yield effects. Moreover, these results from figures 4.3 and 4.4 suggest the existence of potential relationships between the lifetime of the types of equipment and the residual lifetime of the already obtained ones. The multiperiod mathematical program indicates that it is an optimal decision to decide for replacements after the residual years of the currently used equipment are lower than half of the overall potential lifetime. This observation was not

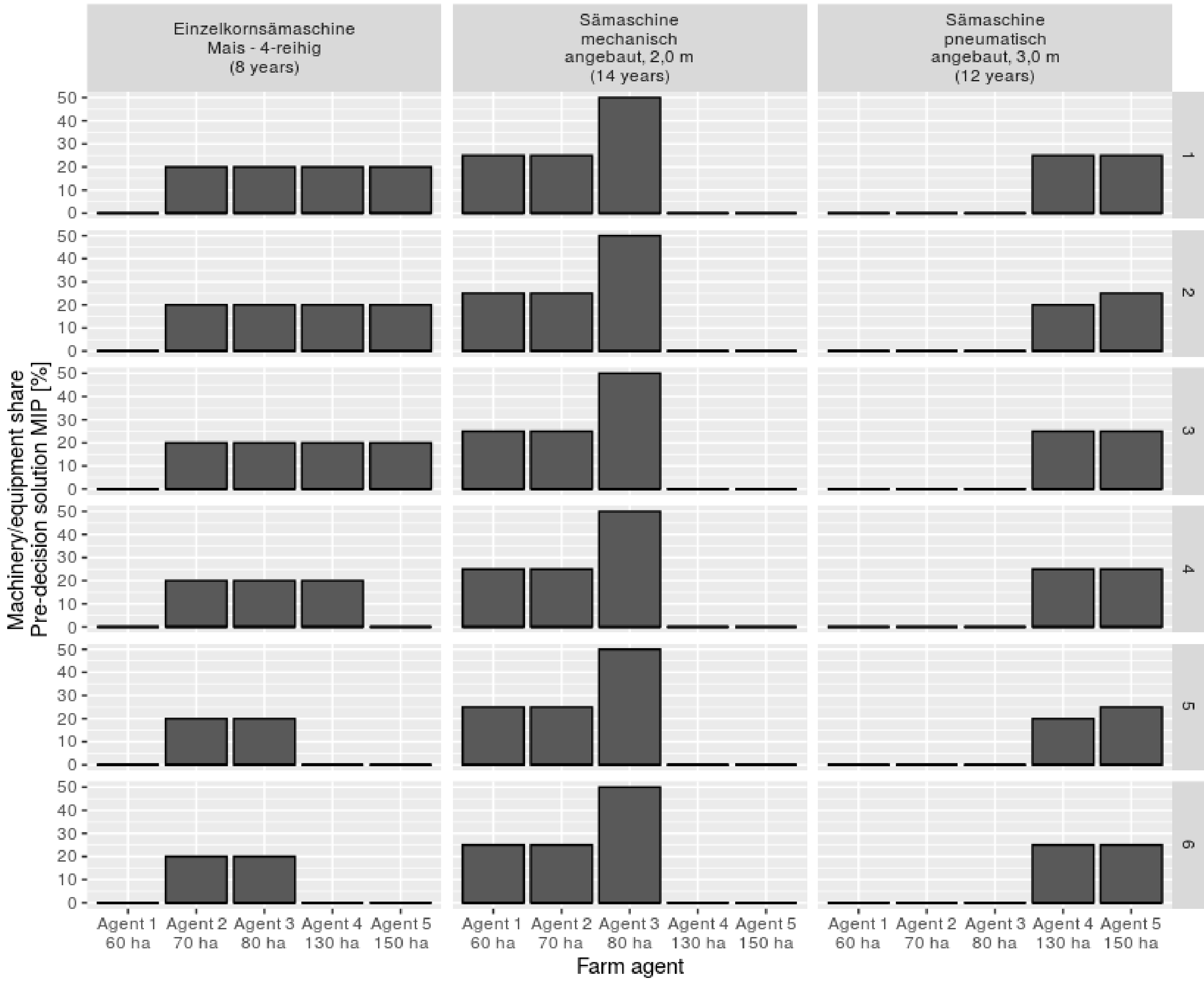

Figure 4.3: *Pre-decision results for the five evaluated farm agents: Demand for shared equipment across "residual value" scenarios for endowed seeding equipment. Scenarios with constant yields.*

further examined in the context of this application, yet, detailed examination of it can be continued by running the same model system for additional residual years of the endowed machinery or equipment.

Simulated association groups

By examining, the results of the pre-investment decisions, it is already possible to anticipate the resulting sharing groups for the seeding equipments. For instance, in the baseline scenario with constant yields (i.e., no yield effect), one sharing group will be conformed consisting of farm agents one, two, and three; these farm agents correspondingly apply for 25, 25, and 50 shares of one unit of a mechanical seeding machine of two meters (*Sämaschine, mechanisch, angebaut, 2,0 m*) and no other conflicting and potential group is observed. An association group for joint acquisition of a maize precision seeder of four rows (Einzelkornsämaschine - Mais - 4-reihig) is only possible at the baseline scenario

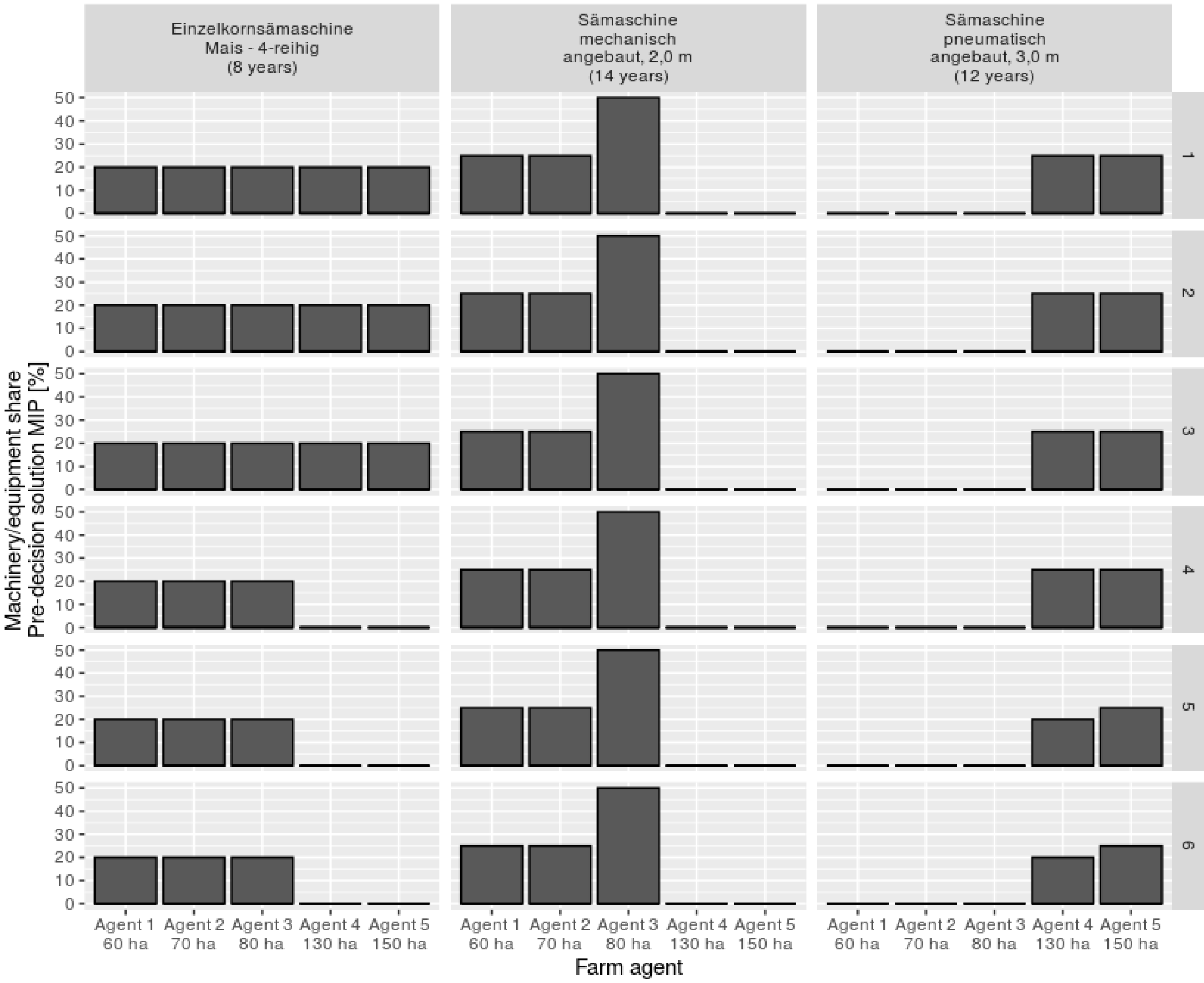

Figure 4.4: *Pre-decision results for the five evaluated farm agents: Demand for shared equipment across "residual value" scenarios for endowed seeding equipment. Scenario with yield effects.*

with a yield effect given that all farm agents have looked for the acquisition of a 20 percent share of a unit of maize seeding equipment of four rows.

Table 4.2 shows the final farm agent association groups that were formed following the rules implemented in the Python algorithm of the external interaction module. The results communicated from the interaction algorithm towards MPMAS are consistent with the results of pre-investment decisions showed in figures 4.3 and 4.4. The table shows the farm agent id (one to five) and the associated share acquired in the joint acquisition of machinery (in parenthesis).

4.1.9 Discussion

This section presented the functioning and potential of a MPMAS external module for joint machinery acquisition among farm agents. The external module is based on the-

Scenario	Residual life of seeding equipment (years) endowed to agents with 130 and 150 hectares	Precision seeder - maize - 4 rows (Einzelkornsämaschine - Mais - 4-reihig)	Seeding machine, mechanical attached, 2 meters (Sämaschine, mechanisch, angebaut, 2,0 m)
Residual00YieldConstant (baseline)	No endowment		1(25), 2 (25), 3 (50)
Residual01YieldConstant	1		1(25), 2 (25), 3 (50)
Residual02YieldConstant	2		1(25), 2 (25), 3 (50)
Residual03YieldConstant	3		1(25), 2 (25), 3 (50)
Residual04YieldConstant	4		1(25), 2 (25), 3 (50)
Residual05YieldConstant	5		1(25), 2 (25), 3 (50)
Residual06YieldConstant	6		1(25), 2 (25), 3 (50)
Residual00YieldEffect (baseline)	No endowment	1(20), 2 (20), 3 (20), 4 (20), 5 (20)	1(25), 2 (25), 3 (50)
Residual01YieldEffect	1	1(20), 2 (20), 3 (20), 4 (20), 5 (20)	1(25), 2 (25), 3 (50)
Residual02YieldEffect	2	1(20), 2 (20), 3 (20), 4 (20), 5 (20)	1(25), 2 (25), 3 (50)
Residual03YieldEffect	3	1(20), 2 (20), 3 (20), 4 (20), 5 (20)	1(25), 2 (25), 3 (50)
Residual04YieldEffect	4		1(25), 2 (25), 3 (50)
Residual05YieldEffect	5		1(25), 2 (25), 3 (50)
Residual05YieldEffect	6		1(25), 2 (25), 3 (50)

Table 4.2: *Resulting farmer association groups after interaction module communicates with MPMAS. Code: Agent id (share of equipment), e.g., 2 (20) means that agent two acquired a 20 percent share of the equipment.*

oretical principles relevant to group composition and communicates with MPMAS in a two-decision stage approach. The use-case results indicated that the evaluated farm agents showed a willingness to acquire less than 100 percent of the capacity provided by the different seeding types of equipment. Moreover, the willingness to acquire shares of the different equipment types allowed the simulated farm agents to form investment groups when specific conditions of complementarities in investments, preferences for small groups, and average distances between farm agents were fulfilled. Even when the application here showed established random assignments of a homophily measure (distances between all farm agents), the external module allows for more complex patterns of homophily or distance measures. For example, data from social networks (e.g., Twitter, Facebook) or cellphone communication networks typically provide patterns in which different social groups interact with each other. This information, accessible with relatively low cost, can be sampled and employed for more complex parameterization in the external script for agent interaction in a scenario-based approach.

Capturing the adequate investment cost on the technology share was possible for the pre-investment decision. Given that it is precisely in the pre-investment decision (i.e., first decision stage) that the dynamics of interaction between farm agents are defined, the presented results from the study case show an adequate formation of association groups in joint machinery acquisition, provided the conditions coded in the interaction algorithm and discussed in the theoretical section of this chapter. In the second and final decision stage (i.e., the effective implementation stage after the interaction outcome is provided by the external module), the financial balances do not yet capture the cost of the shares paid by the farm agents that successfully share a technology. Even when this observation does not affect the group formation dynamics for buying and sharing technology that were shown in the use-case application, it is important to transparently communicate that the representation of the cost of the equipment share in the pre-investment decision overestimates the available liquidity that the farm agents have in the second and final decision stage. In a way, the farm agents acknowledge the cost of their share of technology in their whole-farm financial balance but without knowing that they would not need to effectively pay for it if a sharing group is eventually formed.

The reason for considering the investment cost of the share of the technology only in the pre-investment decision was a technical difficulty in carrying the information from one decision stage (pre-investment decision) to the next one (the second and final decision) in the Mpmasql4 tool. The external interaction algorithm is the responsible to perform the assignment of assets from the pre-investment decision stage towards the second and final decision stage. However, in the second and final decision stage, investments in assets subject to interaction need to be limited by the inserter "*time decision stage data*" of the Mpmasql4 tool in order to introduce an upper bound of zero (and not allowing further investments in assets subject to interactions). By settling these activities to zero, it is communicated to the financial balances that no share of equipment is acquired, regardless of the interaction algorithm's outcome in the first decision stage. A potential solution is to adapt the Mpmasql4 code to allow the "*if(x,y,z)*" function to recognize inserters as a first argument. Currently, the "*if(x,y,z)*" function in the Mpmasql4 tool allows only the use of inserters as second or third arguments. Allowing the recognition of inserters in the first argument of an "*if(x,y,z)*" function would permit adapting the Mpmasql4 model in a way that auxiliary variables are activated when the farm agent applies for a share of equipment in the pre-investment decision stage. The auxiliary variables – that would represent one-year "asset clones" of the proper machinery subject to sharing – are then subject to interaction by the external module and will necessarily be assigned in association groups "as if they were" the original machinery under sharing conditions. By combining the use of the inserter "*time decision stage data*" as the first argument of an "*if(x,y,z)*" function and a second inserter ("*agent assets capacity*"), it is possible to communicate to the second decision stage that there is a need to pay for a share of equipment in case the interaction algorithm has formed a group of agents with joint investments on machinery. Making use of the already coded Mpmasql4 inserter "*agent asset capacity of age*" would not work, since the use of clone assets requires one year of lifetime information (to be considered only in one simulation period). Utilizing the same lifetime of the full asset would affect the optimal decision of the farm agent regarding its interaction incentives.

Nevertheless, the application here showed revealed that there are cases in which simulation of interactions can still be reasonably performed even when data is difficult to obtain (as it is for the case of the functioning dynamics of farmers association groups). With general theoretical and adequate empirical observations, it was possible to simulate interactions in equipment sharing. Moreover, it was shown that the programmed external module for agents interactions can adequately capture several simultaneous sharing groups with different equipments.

The application here presented can be further extended by considering a full uncertainty analysis. Different combinations of selling prices of crops, fuel costs, or machinery costs can potentially modify farm agents' willingness to acquire shares of machinery and their corresponding capacities. Additional farm sizes should also be evaluated as the farm size plays a role in the demand for equipment's capacity.

Moreover, future efforts of representing farm machinery acquisition should put emphasis in capturing alternatives approaches in representing the lifetime of farm machinery; currently, the Mpmasql model employed in this chapter considers that farm equipment and machinery can be utilized in the range between 8 and 12 years depending on the equipment considered, after this lifetime the machinery can no longer be employed in any production process. Nevertheless, farmers typically perform fieldwork operations with equipment and tractors beyond their corresponding accounting lifetimes. Considering the interplay between higher repairing and maintenance costs and more prolonged use of the equipment should play an important role in representing actual asset holdings.

The current presentation of the external module's use for agent interaction did not consider that there may exist markets of used farm machinery. The current Mpmasql4 tool of the MPMAS software offers the opportunity to engage in modeling markets of used machinery; a representation of the selling and buying dynamics of used farm equipment would further enhance the analysis of farm machinery cooperation, yet, a careful consideration of information asymmetries and quality uncertainty (Akerlof, 1970) would be required.

Chapter 5

General discussion and conclusions

5.1 About this Ph.D. thesis

The research documented in this Ph.D. thesis contributes to the Research Project "Regional Climate Change" (*DFG-Forschergruppe 1695 Regionaler Klimawandel*) by employing, enhancing, and examining the modeling tools designed to understand the vulnerability and sensitivity of adaptation strategies of typical farm systems to climate change in the context of the ongoing structural change in agriculture in Southwest Germany. In the previous chapters numerous optimization and simulation results were showed and discussed; these results revealed complex adaptation decisions of land-use outcomes and machinery investments to potential climatic manifestations at the farm level. In the following subsections the general findings are discussed and future research requirements are highlighted.

5.2 What are the lessons? Providing answers to the research questions

5.2.1 How do simulated land-use patterns and farm machinery investment decisions respond to various climate change scenarios implemented in the MPMAS model component of the bioeconomic modeling system MPMAS-XN?:

The efforts exerted in subchapter 3.1, "Dynamics effects of shifts in fieldwork time on land-use and machinery acquisition," treated the first research question. In the context of this research question, this Ph.D. thesis contributed to the construction and with the first assessment of the sensibility of the recursive-dynamic MPMAS model component of the bioeconomic system MPMAS_XN for the Central Swabian Jura region in Southwest Germany. The simulation experiments' results assessing potential climate change responses in the MPMAS model component suggested that –for the current parametrization and evaluated farm size– farm machinery investment decisions are less responsive than the decisions to alter the land-use patterns when changes in external conditions (e.g., yield courses, trends in the fieldwork timing) are evaluated through different climate change scenarios.

The simulations addressing the MPMAS model's for the region of Central Swabian Jura revealed that it could be expected that farmers engage in important adaptations in their land-use patterns whenever shifts in the ideal dates for fieldwork operations result in collisions of several required work operations within a specific time window. Nevertheless, the model is currently parameterized to respond to the ideal fieldwork timing. In reality, farmers may deviate from the ideal timing for fieldwork operations; in this regard, field operations' timeliness is not yet captured in this model. Farmers may be willing to sacrifice a certain yield level by delaying their fieldwork operations. Such types of practices are typical for seeding or fertilization activities.

Moreover, the lessons from the simulation analysis performed for answering the first research question are that the flexibility of the modeling approach and the detailed interrelationships of resources represented at the agent-decision module of MPMAS can result in outcomes which are complex and not always foreseen; it is the author's opinion that complying with the strive for improved understanding and communication of results in the use of the MPMAS_XN system will require complementary stress simulation runs of single-agent decision matrices across the different scenarios evaluated and design points of the uncertainty analysis. The improved multiperiod nature of the agent-decision module of MPMAS, in combination with the recursive-dynamic modeling approach, offers a unique and perfect opportunity for this; expected farm management plans for future years (T) are directly observed and can be further contrasted with effective/implemented simulation plans (P) in the light of the recursive-induced surprises ($t_p = 1, 2, 3, .., T$; $\forall$ p $\in$ P) derived from the different scenario simulations.

5.2.2 How do farm machinery investment decisions and economies of size derived from farm mechanization are shaped across a wide range of farm sizes in the context of distinctive time windows affecting the performance of weather-dependent fieldwork operations?:

Subchapter 3.2, "Economies of size in farm mechanization," presented an optimization analysis with the aim to provide answers to the second research question of this Ph.D. thesis. Farm machinery investing decisions were assessed at several farm sizes, allowing learning about patterns in which machinery acquisition may develop in the course of agricultural structural change and further impact the achievement of economies of sizes in farm mechanization in Germany. The optimization analysis performed for the study of farm machinery acquisition highlighted the inherent existence of economies of size enclosed in the data of KTBL.

Furthermore, the constructed whole-farm multiperiod optimization model proved adequate to capture the multiple relationships between fieldwork operations and demand for machinery capacities. The detailed representation of such relationships enriched the analysis and proved relevant in contributing to new insights into how the achievement of economies of size can be modified under changed climatic conditions. The results of the optimization model allowed to observe potential effects of changed climatic conditions on machinery investment costs, returns, costs and machinery acquisition courses.

The current fieldwork day distribution in the Central Swabian Jura corresponds to the estimates provided by KTBL (2010) for climate zone 4. In terms of mean temperature, length of growing season, and number of frost and heat days, the ReKliEs-De model ensemble (Hübener, et al., 2017) suggests that in the business-as-usual scenario (RCP8.5) the future climate in the Central Swabian Jura might correspond to the current estimates of KTBL for climate zone 7. The whole-farm optimization model developed for answering the second research question of this work was then run, evaluated and compared across KTBL climate zone 4 ("current" climate in the Central Swabian Jura) and KTBL climate zone 7 ("future" climate in the Central Swabian Jura).

The model's results showed that tighter time windows for weather sensitive fieldwork operations as represented by the estimates of KTBL climate zone 4 have the potential to result in higher-value machinery acquisition while requiring higher investment (and replacement) costs for the current crop rotation considered. However, this effect holds in specific farm sizes and is not uniform across all of the evaluated farm sizes. Morover, wider time windows for fieldwork operations, such as those that may potentially be found in the future in Central Swabian Jura, allow more substantial exploitation of economies of size. Under these results stronger economies of size effects may be expected in regions where climate change manifestations lead to a widening of time windows for fieldwork and increases in investment cost where it leads to tightening.

The optimization results from subchapter 3.2. showed that economies of size from farm mechanization could be achieved at farm sizes below 180-210 hectares; beyond this size threshold, the results indicate that several farms with distinct sizes can potentially coexist and achieve similar economic returns. However, the results are specific to the particularly requested crop rotation determined in the model in the absence of other factors that may also influence the achievement of economies of size. Besides, the optimization results indicate that tighter time windows for the performance of fieldwork operations may have different effects on machinery investment decisions across several farm sizes. It is not always the case that tighter time windows result in a higher value or more investments in farm machinery and equipment; this depends on the specific farm size analyzed and the utilization degree of the on-farm equipment and machinery of the farm.

Moreover, the investigation developed in subchapter 3.2 led to the delivery of valuable by-products: The need to establish a connection between the MPMAS model and the KTBL online applications for data gathering resulted in fully automatized programming routines that allow web-scrapping and serve as a basis for the further enhancement of the farm decision module, e.g., capturing data on alternative cultivation systems like direct seeding, conventional tillage, or alternative cropping-level options like medium or low yield potentials. The inclusion of additional cropping alternatives, together with a wider selection of cultivation approaches, would enrich the analysis of economies of size, acquisition of indivisible technologies, and incentives for farm growth.

5.2.3 How can farm machinery associations be modeled in the MPMAS modeling framework in the context of scarce data availability?:

The effort of methodological enhancement was based on the implementation and presentation of an external module for the model system MPMAS_XN (Chapter 4) and particularly for the application with the Central Swabian Jura model. Process-based models for climate change adaptation, in order to adequately represent unobserved or “out of the sample” adaptations, should capture the relevant structural dynamics that define the decisions of the object of study. In this doctoral work, the challenge of scarce data availability for the representation of joint investment decisions dynamics among farm agents was treated by making use of theoretical guidelines and empirical observations of farm machinery associations. An empirical validation of the approach remains as a challenge and subject for future research.

The representation of farm machinery associations in the MPMAS modeling framework was based on three elements: i) Conditions of complementarities in investments, ii) preferences for small groups, and iii) measures of similarity (e.g., average distances between farm agents). The implementation of the external algorithm for agent interaction aimed explicitly to address the challenge of data scarcity. Detailed information and data on real-world farm machinery associations’ functioning are typically difficult to obtain (due to data privacy and due to associations based on personal actions); therefore, the approach developed for Chapter 4 was based on considering the identified structural characteristics that drive to group formation, this from a theoretical point of view and observations of farmers’ experiences in publicly available sources.

5.3 Looking forward and future research

5.3.1 Validation

Further methodological challenges remain in assessing the potential effects of climate change in the context of agricultural structural change with the available modeling tools here presented and employed. The validation of the model results in this doctoral thesis was performed utilizing a straightforward and simple comparative approach. Even when the compared results showed that the employed modeling tools derive in outcomes that are comparable with the ones observed in reality, quality comparison data for a satisfactory validation procedure is identified as a point for improvement in this thesis; the scarce detailed data on actual farm machinery management strategies (different types of machinery and equipment used by farmers) is typically not available in public data sources, and individual surveys or direct communication with farmers are required. Nevertheless, the simulation and optimization results here presented complied with the validation pillar of capturing uncertainty in the analysis, which provided robustness of the models’ outcomes up to a certain extent. Also, the results were based on good representation of the structure of the relationships represented in the whole-farm decision module. However, it is important to point out that the decisions that farmers in Germany make in the courses of climate change and agricultural structural change are very much complex, and the models constructed and employed in this work reflect parts of these decisions.

5.3.2 Expectation formation mechanism

The treatment of the topic of expectation formation would require detailed attention in the use of recursive dynamic simulations with the MPMAS_XN bioeconomic model system. In subsection 3.1, the assessment of the responsiveness of the MPMAS model component employed the naive expectation formation mechanism ($t-1$), which is partially dependent on a low-complex framework of crop similarities; in reality, even when farmers do not grow a crop for some years (and therefore do not have an up-to-date observed reference of what is the ideal timing for fieldwork operations), they can gather information from other sources, e.g., neighbors, extension services. Moreover, while not treated in this contribution, the simulated farm agents' learning process should include more complex representations of anchoring effects or additional interaction with other farm agents to capture the speed of adaptation. Future research should also assess the efforts of allowing flexible changes in the expectation formation process during the simulation periods (e.g., an initial naive expectation formation and later a shift towards rational or other types of expectation formation mechanisms), especially when long-term simulations are performed; there is nothing that hinders farmers to change the way the expect future outcomes. A conceptual framework for giving meaning and representing such a subjective behavior is, naturally, a necessary condition before the technical efforts to model it are taken.

5.3.3 Farm machinery management

This Ph.D. work focused on the farm machinery management dimension. Yet, several factors are still abstracted in this treatment. For instance, the modeling approaches taken did not consider elements of pride in machinery acquisition. From the author's literature evaluation and the review of stylized facts derived from farm machinery acquisition in Germany, it was observed that pride plays an important role in the demand for farm equipment. This observation has the potential to alter the farm machinery demand dynamics in the course of agricultural structural change. For instance, in the process of farm expansion and updating of farm machinery and equipment, farmers may acquire a new piece of equipment that provides more-than-the-required working capacity if the subjective valuation plays a role; situations like: "*Why should I buy a 2.5 meters-wide seeding implemented when I can, for some additional capital, acquire a 3 meters-wide one? – I actually need 2.5 meters, but 3 meters-wide looks better*" can perfectly arise. Additionally, preferences for equipment and machinery from particular farm implement producers can play an important role in defining farm machinery's investment costs. These elements are not yet considered in this contribution. These types of decisions are hard to depict, and suggest that detailed attention should be place in the definition and representation of the objective function of the farm-decision module when dealing with different modeling applications.

Moreover, the risk dimension treatment was neglected in the current analysis and left for future research. Experiences from real farmers suggest that the apparent outsourcing of climate-related risk can potentially be associated with preferences for using custom hiring services. In this regard, the enhanced agent-interaction platform for modeling interactions in MPMAS through the Mpmasql4 tool provides a promising opportunity to improve the representation of hiring markets in combination with other options for the acquisition of farm machinery capacities.

Chapter 6

Appendix: Documentation, annexes, references

Contents

6.1 MPMAS simulation model for "Dynamic effects of shifts in fieldwork time on land-use and machinery acquisition". The "MPMAS_XN" model system

This section presents the model design and the parameterization of the submodel MPMAS of the model system MPMAS_XN. An overview of the model system MPMAS_XN is provided. A description of the externals script to define an algorithm for the simulation of farm to farm cooperation in machinery acquisition are provided in the supplementary materials. Detailed results drawn from the verification of different model MPMAS components are provided in a separate file in supplementary materials.

6.1.1 Overview, design concepts and details of the model system

The Expert-N (XN) model

Expert-N (XN) (Biernath et al . 2011) is a modular modeling framework that makes the simulation of diverse soil and plant process-model combinations. Plant processes such as phenological development (e.g., ideal dates for sowing or harvesting), photosynthesis, canopy formation, growth of aboveground and root biomass, crop senescence, transpiration, and nitrogen uptake can be modeled with one of the generic plant models CERES, SPASS , or GECROS or others. Soil processes can be simulated flexibly integrating process models from HYDRUS, DAISY, LEACHN, SOILN or CENTURY among others. The EPIC model takes soil loosening and compaction routines. Thus, XN allows the systematic analysis of various combinations of plant and soil processing routines (Troost et al., 2020).

The Mathematical Programming-based Multi-Agent Systems model (MPMAS)

The MPMAS software (Schreinemachers and Berger, 2011; Troost and Berger, 2016) is an agent-based modeling software that stands in the agricultural economic tradition of using mathematical programming to represent the production and land use decisions of farm managers. The main model entity in MPMAS is the farm agent, and it represents a farm business or farming household's decision-maker. At each decision point, usually set in terms of years before the beginning of a cropping season, MPMAS agents solve a mixed-integer programming (MIP) problem to determine the optimal farm-level decisions (production, investment, and consumption) subject to a set of constraints (e.g., policy, crop rotations, capital endowment). By using a mixed-integer programming model, MPMAS allows representing complex relationships between the potential activities and available resources on the farm, e.g., competition for resources for the performing of fieldwork operations, or the requirement of capital or other endowments. The new version of MPMAS enables explicit inter-temporal multi-period planning and recursive simulations, where farm agents are able to establish long-term farm plans and are able to recursively revise these plans.

The model system MPMAS-XN

A detailed description of the conceptual overview and simulation flow of the integrated model system MPMAS_XN is provided in Troost et al., (2020). Here the main communication between both models is highlighted.

Each MPMAS farm agent solves an intertemporal whole-farm decision problem once a year and decides on the farm investment and cropping for the upcoming season. Agent decisions at this strategic and tactical decision stage are taken based on expectations on crop yields, actual fieldwork action dates, and actual nitrogen demand for each crop management strategy formed from observations in previous years. At the same time, agents consider the next 10-20 years to recognize the future benefits of current investments and effects on future production opportunities.

Once the farm agent has made its land-use, investments and other relevant decisions, MPMAS communicates the crop and management strategy choice XN. MPMAS and XN share a common grid-based representation of the simulated agricultural area (e.g., one ha), this allows that the communication of the crop management strategy choice is provided for each map cell to XN. The crop growth model performs a continuous simulation of plant and soil processes throughout the whole coupled simulation that is just paused to allow the field management module to communicate with MPMAS at the point of the yearly decision, while all information on soil and plant state remains in memory and hence soil conditions are taken over from one season into the next.

Before the farm agents solve their next decision problem at each yearly decision point, XN communicates to MPMAS the resulting modeled yields, management dates, and fertilizer quantities. Based on this information, farm agents in MPMAS update their expectations concerning yields, fieldwork dates, and fertilizer demand that they associate with individual cropping plans and use them to decide on their production and investment plan for the following year.

The model system MPMAS_XN in this thesis

The objective of utilizing the MPMAS submodel of the system MPMAS_XN in this work is to explore the potential in representing likely adaptation decisions towards farm-level reorganization, land-use decisions and performance outcomes in light of climate change scenarios. The model is constructed to be able to simulate adaptation decisions that arise as a result of shifts in the ideal dates for performing specific fieldwork operations (i.e., sowing, harvesting, fertilization).

In the current thesis, coupled simulations between MPMAS and XN were not performed. Instead, XN's functionings was reproduced by externally providing yield courses and trends of ideal dates for specific field operations thorugh simulation periods, and evaluated this input into MPMAS. The emphasis of the design of the Central Swabian Jura MPMAS model, as well as the experimental design proposed in the chapter "Dynamic effects of shifts in optimal fieldwork time on land use and machinery acquisition", is made in a way that they allow to to recognize potential responses of farmers to climate change manifestations in the research area of the Central Swabian Jura by representing their farm system and by focusing on the adaptation of the land-use and machinery acquisition decisions. In general, the long-term scenarios should allow an improvement of the understanding of the sensibility of the linkages between climate change and variability and farm-level reorganization and land-use.

Entities, state variables and scales

In the model system, real-world farmers are represented by model agents as entities that behave and can potentially interact with other model agents. Agents are distinguished from other agents in their household composition (career, age, marital status), their asset endowment (age and quantity of asset). Additionally, the agents can be distinguished by their farm size, the characteristics of their plots and agents' characteristics can also be grouped in cluster and populations, which in turn allows for the distinction of expectation formation processes.

6.1.2 The farm decision model: Design concepts

Objective function

The agent decision module of the MPMAS model consists of a multiperiod Mixed Integer Programming Model. In this section, the nature of the objective function of the mixed-integer programming problem is presented.

The assumed objective in the solution of the decision problem is to maximize the discounted cash withdrawals that agents (agents are considered heterogenous simulated farm managers) perform at the beginning of a given period. Right after a specific period has passed and before a new period begins, the simulated farm agents decide whether to withdraw cash (for nonfarm expenditures, living costs, and other non modeled purposes) or to make use of the available cash to i) cover payments for long-term farm investments (e.g., acquisition of machinery), ii) provide for the necessary liquidity to cover payments for farm production (variable costs) or iii) both, long-term farm investments and expenditures for short-term farm production. It is expected that i) farmer agents will plan in a way that their planned investment and production choices will allow them to withdraw as much cash from their farm business and ii) farmer agents will plan in a way that their planned investment and production choices will free up money earlier due to the existence of the discounting factor and the with it implied and assumed preference for resources to-day than in the future. The trade-offs between earlier withdrawals and fewer withdrawals overall are a function of the discount rate. We also include the terminal values for owned assets (machinery and equipment) in the objective function. These values are calculated based on the acquisition cost of the asset and using a linear depreciation rule.

Recursive-dynamic simulation with multi-period planning horizon

In a recursive-dynamic model, farm agents make a plan for their activities over a specific time frame, possibly several years or agricultural seasons; they implement the immediate actions according to the plan after time has passed, they observe the results of those immediate actions taken before and, if necessary, they revise their plan (in coherence with the nature of the objective function), they implement the next actions of the (potentially updated) plan, observe the results again, update their plan, and so on.

Depending on how forward-looking the decision-maker is, the planning horizon may be much longer than the interval between the revisions of the plan. If intertemporal effects have to be considered, the planning horizon is usually longer than one year: Decision-makers make multi-year plans. Nevertheless, the modeled agents implement only those parts of the plan that are to be implemented before the next point of decision is reached. When that new point of decision has been reached, they will observe the outcomes for the first period and revise their plan according to the outcomes.

In the functioning of a typical and simple recursive simulation, there is a simple, clear-cut season. Farmers sow and manage before they sow the crop for the next season. In the simple representation of a recursive simulation and decision occurences, harvesting field-work operations are performed at the beginning of the following season (correspondingly, the next decision point or simulation period) before sowing the up the coming crop. We further consider that the harvested crop is directly marketed (respectively stored for consumption) after harvest. Given this mentioned order of activities, the point in time where the decision making takes place (the switch between periods) is conceptually located directly before harvest. The part of the multiperiod plan that is directly implemented after the plan has been made then includes:

1. Harvest of the standing crop and marketing/consumption of the harvest,
2. investment in new assets,
3. cropping plan,
4. field operations, sowing, management.

The reason of this is because according to our assumption this sequence of decisions involves no surprises: it is safe to assume that all of these decisions will work out as planned at this point of time, because at this point farmers know the yield of the standing crop, know the prices for which it can be sold, know the price for investment goods, know the prices for the inputs to be bought. The MPMAS model for the Central Swabian Jura behaves, in principle, in the here described fashion, yet, more specific line of occurences of the harvesting and selling times are represented (See section of Harvest and selling balances below for a detailed description).

Land use

The current MPMAS model allows the farm agents to engage in crop production. The available crops are winter rapeseed, winter wheat, winter barley, spring barley, silage maize, and fallow. Following the initial model version (static equilibrium agent-based model) created by Troost (2014) and on which this model version is based upon, the management plans were determined from standard recommendations of German extension services (KTBL, 2010; LEL, 2012; LfL, 2012) and cross-checked and updated in expert interviews, survey results, and observations on the field measurement sites. Three fertilization schemes are (only mineral fertilizer, with pig manure and with cattle manure) and two tillage regimes (plow tillage and low tillage using rotary tillers) are distinguished. For the two spring crops, spring barley, and silage maize, management plans with and without winter cover crops (field mustard) are included. Different pesticide use levels are not distinguished; instead, a standard plant protection practice for each crop is established, the reason for this assumption is that it was not possible to simulate the yield effect of pesticide use. Management plans determine the number of physical inputs required, the necessary fieldwork (tillage, sowing, fertilization, plant protection, harvest), and its timing. Except for animal manure, physical inputs are multiplied by prices and aggregated to direct cost.

In terms of the mathematical programming model, the land use options consist of pre-defined combinations of i) a crop, ii) a crop management plan, iii) a crop history of the plot, iv) the soil type of the plot and the planning period in which the decision is to be taken.

Crop rotations

The model component MPMAS of the MPMAS_XN model system was implemented with a spatially and temporally explicit representation of crop rotations. The focus in the implementation was made in terms of capturing and keeping track of the characteristics of each individual cell of the shared map (landscape) for the purposes of running a complex inter-temporal and coupled model system, this, with the aim of achieving a more versatile planning that allows for differences in crop shares across the planning horizon and the plot's past history. In addition, certain rotational constraints are due to timing incompatibilities, i.e., a preceding crop is usually not harvested early enough to allow subsequent crop potential to be sown, which may be altered by climate change.

The crop rotation representation was established following explicit rotation rules obtained from expert interviews recorded by Troost (2014) for the research region of the Central Swabian Jura. The crop rotations consider the following formats:

1. Crop rotation formats considered:
    (a) Direct next-year non-allowance: considers crops that can not be grown after another crop has been grown in the same plot in the previous year.
    (b) Continuously growing classes: Considers that there are crops that belong to the same class (i.e., wheat and barley belong to a "cereals" classification), and the crops belonging to this class can be grown for no more of "n" seasons/years continuously.
    (c) Breaks: Considers that a crop can only be grown in a plot if other crops (or the same crop) have been grown with a break of at least "n" years.

We additional include the following rules of rotation:

1. Rules:
    (a) Rapeseed needs at least two-year break after itself and can be grown after barley (spring and winter), fallow and winter wheat
    (b) Winter wheat can be grown after barley (spring and winter), silage maize, winter wheat, fallow and rapeseed

(c) Winter barley can be grown after spring barley, fallow, winter wheat and rapeseed

(d) Spring barley with the intermediate crop can be grown after barley (spring and winter), fallow, winter wheat and rapeseed. Spring barley without intermediate crop can additionally be grown after silage maize.

(e) Silage maize with intermediate can be grown after barley (spring and winter), fallow, winter wheat and rapeseed. Silage maize without intermediate can additionally be grown after silage maize.

(f) Cereals can be grown a maximum of 4 years continuously

(g) Silage maize can be grown a maximum of 5 years continuously

(h) Winter wheat and spring barley can be grown continuously two years. Winter barley can not follow after winter barley.

Based on these rules, we created plot histories that represent sequences of crops in time for five years in the past (e.g., year $t-5$ crop $c1$ was grown, year $t-4$ crop $c2$ was grown,..., until $t-1$). These plot histories were constructed using a cartesian product matrix for all the crops, and later, a program was written in Python 3 to evaluate each crop sequence. The evaluation of each crop sequence has the objective to either accept or discard the sequence on the basis of its empirical possibility; if the crop sequence in time does not violate any crop rotation rule that was specified above, then we accept the sequence as a potential crop rotation in time; otherwise, it is discarded and does not become a valid crop sequence.

When a crop is planned to be grown in a specific plot (a crop produced with specific given management), the model system makes sure that this crop should only be grown in available plots that have crop histories that do not contradict the rotation rules. For example, plots that have already seen wheat grown twice in the last two years or plots in which cereals have been grown already four years continuously will not be an option for growing winter wheat in the next cropping plan established.

Furthermore, once a new crop is effectively grown in a plot, the history of that plot will change and MPMAS will update its history in a way that in the following simulation period the cropping decisions are established in consideration of the cropping decisions realized in the past. In this way, we make sure that the recursive simulations are up to date with the changes in the plot characteristics. In this model configuration, land classes can be dynamically changed by the decisions of agents. Farm agents can decide to grow crops in a plot of land (i.e., in one hectare) in which a specific crop was grown in the previous season; in order to consider and capture dynamic changes of land classes, the plot history is recorded. A plot history determines – based on typical and relevant crop rotation sequences of the study areas - the set of suitable crops and can be grown in the specific plot of land for the immediate following cropping season in which a crop decision is taken. Once a new suitable crop is grown in a plot of land, the soil history of a plot is updated, and the plot and its newly updated history serve as the basis in which new cropping decisions are made. The soil types in the soil maps correspond to several "*soilmapids*", which are constructed as a function of generated soil histories for the crops and soil types (nutrient response units; NRUs. Refer to the MPMAS manual) the model.

For the creation of the crop rotation sequences and corresponding crop histories, an automated process was coded with Python (v.3.6.5, Anaconda, Inc.), between April and

July 2018. The Python code requires the libraries *openpyxl* and *sys*. The source code, provided in a separate file, consist of the following building blocks:

1. Arquitecture of source code for crop rotation and crop histories implementation:
    (a) Communication between python script and spreadsheet
    (b) Definition of parameters and initialization of program based on spreadsheet value-definition
    (c) Definition of the cartesian product
    (d) Filtering crop sequences based on the list of the cartesian product
    (e) Creating the format required by MPMAS
    (f) Creation of new histories (.txt files to be uploaded in a server in communication with Mpmasql4)

The code was generalized for its use in several applications (different crops, crop rotation formats), and it feeds from an excel spreadsheet with a specific and non-modifiable format in which all the necessary information for the creation of crop histories needs to be provided by the modeler. Please refer to the *ReadMe* file provided in the supplementary material for further information.

Input balances

Apart from labor, tractor, and machinery capacity, the production of crops requires a number of explicit inputs (seeds, herbicide, pesticide, etc.). To capture the requirement of inputs, input balances were created, in which the demand for input per hectare depends on the number of hectares of each crop considered in our model system. The overall amount of each input is then converted into monetary units based on expectations of prices for each of the future planning periods and effective prices for each simulation period. For the simulations here presented, the expected prices and effective prices were the same. Nevertheless, the model system allows their distinction if the application requires adaptation of the plan due to differences between expected and effective prices. The converted monetary values are all added up and communicated to the financial balances of our model system.

Harvest and selling balances

In Central Europe cropping seasons overlap, and there is no clear distinction between cropping seasons. Yet, in this model version, harvesting and selling balances need to capture the timing in which harvesting and selling occur correctly. The MPMAS modeling framework for recursive simulations takes July first as the point in time in which the simulated farm agents take a planning decision. Given this, it is considered that winter crops grown between July and December of $t = 1$ are harvested between July and December of $t = 2$, and, given that the planning decision is only made at the beginning of every year's July, the yield can be sold two years from now, at the beginning of July in $t + 2$. The same approach is taken for spring crops; spring crops grown between January and July in year $t = 1$ can only be harvested between July and December of the same year; notice that the decision of growing a spring crop between January and July in the year, say, 2009, was made in August of 2008 in our modeling framework. Given that the planning decision is specifically made at the beginning of every year's July, the yield can be sold two years from now at the beginning of July in $t+2$. The schema presented below summarizes these dynamics, and, based on them, we implemented them in the code of the submodel component MPMAS of the system MPMAS_XN.

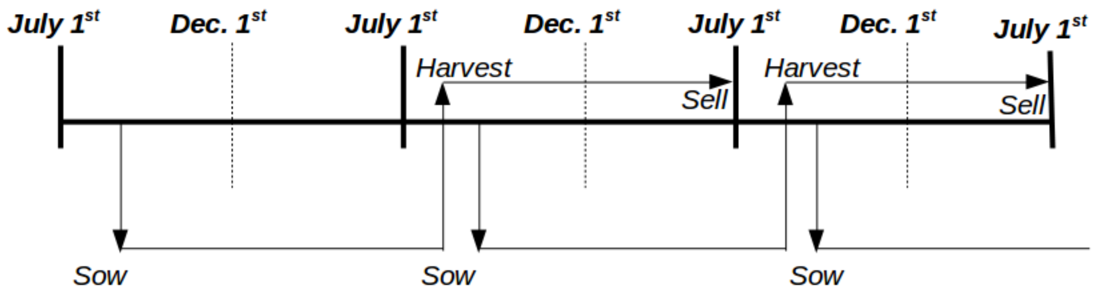

Figure 6.1: *Example of harvest and selling dynamics*

Dynamic fieldwork demand

Every time a simulated farm agent decides to grow a specific crop, many adequate fieldworks need to be performed so the crop can effectively be produced. Fieldwork can take the form of, for example, sowing, spraying, harvesting, working crop residues, among others. Moreover, when a farm agent needs to perform, for instance, harvesting operations on a specific half month (this is the established time resolution), it has the freedom to either choose to harvest with a combine harvester of 125 kW, a combine harvester of 175 kW or to harvest making use of both (we refer to the combination of field operation with a piece of specific equipment as a fieldwork activity and the general fieldwork operation only as fieldwork type). In either case, the corresponding machinery and equipment need to be provided. The constrained optimization process defines the decision of how the fieldwork is performed (either with the 125 kW or 175 kW combine harvester). Most of the fieldwork activities correspond to aggregates of a main equipment (e.g., a seeding equipment of "m" meters wide, and a tractor of a specific tractive power - kW level, also, wider equipments typically require higher tractive power)

The definition of the demand for fieldwork in the fieldwork balances is made in terms of the frequency in which a single hectare of grown crop needs to be worked; i.e., harvesting requires that one hectare be worked once. The supply of fieldwork is made in terms of hours of fieldwork that can be provided; in one hour of fieldwork "h" hectares can be effectively worked (with the corresponding machinery and equipment specification of the selected fieldwork activity).

Furthermore, the fieldwork balances implemented in the model capture the possibility that fieldwork dates might shift due to climate change. Modified growing periods as a result of climate change have the potential that the timing for performing weather-dependent fieldwork in agriculture can undergo relevant revisions.

For Southwest Germany, the state of a longer growing season can suggest two differentiated appropriate fieldwork responses depending on if the crop in question is winter or a spring crop. For spring crops, it is expected that the elongation of the growing seasons results in earlier sowing and earlier harvesting. For winter crops, the longer growing seasons due to hotter temperatures will likely shift the buffer of days in which it is adequate to sow forward, meaning that later sowing fieldwork activities will be expected. Harvesting of crops is expected to be performed earlier in the year due to early maturity.

The first time that farm agents decide on their upcoming farm plans, an initial expectation is externally provided for the specific date in which fieldwork should be performed (e.g., ideal dates of sowing, bounded to phenological development stages, BBCH). Tentative sowing dates are expressed as a function of accumulated (for spring crops) or expected remaining (for winter crops) growing degree days and are based on a record of six previous years (Troost et al., 2020). The farm agent plans its farm operations into the future with these date expectations (10-year planning horizon) until the next decision point is reached. It is important to notice that the farm agent established its fieldwork plan based on ideal fieldwork operation expectations. The information on the best point in time of the year in which the fieldwork operation should have been performed is only relevant for the upcoming point in time in which the farm agent is expected to make a new planning decision (i.e., the agent can not anymore change what it has implemented). At the moment in which the agent has the possibility to adjust its farm planning through a new decision, it will take into account the real, previously observed, optimal point in time in which the fieldwork type should be performed based on the previous observation and the error of its previous expectation. Depending on the type of expectation considered in the modeling system, the agent can show constant, naive, double exponential smoothing ,or adaptive expectations. For the simulations here presented, naive expectations are considered.

If a date at which the farm agent expects that the fieldwork should be performed falls between the boundaries of any specific halfmonth, the corresponding crop production will have a requirement for fieldwork on that halfmonth. For example, if the date expected to perform harvesting tasks corresponds to the day 226, the harvesting demand will take part in the halfmonth 15 (with day boundaries 212-228). If the date at which the harvesting fieldwork is expected to be performed moves to the day 229, then the harvesting demand will take part of the halfmonth 16 (with day boundaries 228-243).

In this dynamic model system, not all fieldwork operations are subject to shifts due to climate change effects. Most plant protection operations do not depend on plant growth (except for pre-sowing herbicides fieldworks), but they depend more on pest pressure, and this element is not modeled in the crop-growth model of XN. Also, dates for fertilization operations are modeled by XN as being bounded to phenological stages of development, but this does not apply to all of the dates; the first fertilization in Spring is more dependent on the end of the frost period and restart of the plant growth. Ideally, this date should be best linked to a temperature pattern, yet, this has not yet been implemented. Therefore, ideal dates for plant protection and the dates of only the first fertilization operations are fixed.

Technical note on the implementation of the dynamic fieldwork in Mpmasql4: The inserter that controls the time in which a fieldwork should be performed is: agent. expectations. cropping attribute related to the agent's expectation about a user-defined attribute of a cropping activity. The initial expectation has its origen in the table EXTERNAL CG INFO MULTIPERIOD. During the simulation, the expectations are updated using the chosen expectation mechanism based on either the result of the crop model (XN) if coupled or from data in the table EXTERNAL CG YIELDS if an exogenous yield time series (BIOVERSION = 3) is used. The arguments are: cropManagementID, NruID (MIP internal soil ID, in most cases = soil map id), and name of attribute. User-defined attributes for cropping activities are defined in the cfg file with the entry EXTRA CROPACT CHARACTERISTICS and must appear as columns in EXTERNAL CG INFO MULTIPERIOD (and EXTERNAL CG YIELDS if used)

Weather dependency

Each fieldwork activity in this model version requires the availability of the required pieces of equipment, labor, and tractive power during the expected number of days within our time resolution of half-months, in which there is suitable weather for the type of fieldwork. Suitability of weather for fieldwork is determined using the KTBL classification of types of fieldwork according to weather sensitivity level. The levels range from 1: very high demands on the weather to 6: not sensitive to weather, and are estimated with likelihood of occurrences of 60, 70, 80, and 90 percent for twelve sub regions in Germany and distinguished additionally by soil resistance types. These distinctions define the corresponding expected days with suitable weather in each half-month (Troost, 2014).

Equipment capacities and fieldwork activities

The equipment capacities are distinguished by i) the type of equipment, ii) time slot, iii) weather level, iv) soil resistance, and v) planning period. Fieldwork activities demand equipment capacity in the form of time (hours), and growing crops defines the number of hours required based on service per hour (hectares achieved per hour) that single fieldwork activity can to provide (i.e., a fieldwork activity can take the form of sowing with two-meter wide seeding equipment by using a 45 kW tractor and this single activity can achieve "h" number of hectares per hour).

Here it is assumed that a day with weather suitable for the most weather-sensitive fieldwork is also suitable for less sensitive fieldwork; using equipment in days with level 1 weather also reduces the capacity of that equipment for level 6 weather. Additionally, the evaluated soil resistance determines if fieldwork activities that perform on higher soil resistances should be considered for demanding capacity of equipment; here, it is assumed that the time to perform fieldwork on harder soil resistances is also suitable to perform fieldwork on lighter soil resistances.

As examples, fieldwork types like harvest or collection of residues are very weather dependent but not dependent on soil resistance - the soil resistance is not relevant in the definition of the timing required to perform the fieldwork. On the other hand, applying mineral fertilizer or plowing are fieldwork types that are less weather dependent, but in these operations, the soil resistance becomes relevant.

The equipment capacities in the MPMAS model are additionally distinguished by soil resistances. The fieldwork balances define the interaction between the demand for fieldwork and the supply of it (in terms of hectares to be worked - one hour of fieldwork manages to complete "h" hectares).

All the machinery and equipment capacities are calculated by multiplying the number of field days for each level of weather sensitivity and soil resistance at every half month with the available equipment units and the maximum daily hours of technology use (subject to uncertainty analysis).

Every crop that is grown requires that fieldwork be performed on the plot in which it is grown, this plot can have a specific soil resistance (defined by the soil type in which the crop is grown). Even when, for example, the fieldwork activities of harvesting with either a combined harvester of 175kW or with a combined harvester of 125 kW (two different fieldwork activities) are not considered to be a soil resistance-specific fieldwork activities, the work needs to be performed on a plot with a determined soil resistance (i.e., light, medium, hard). In terms of the Mpmasql4 implementation, this is the main reason of why all fieldwork activities that are considered as being not soil resistance-specific are constructed with iterations over all soil resistances. On the other hand, fieldwork activities that are soil resistance-specific can only be performed/executed on plots that have their corresponding soil resistance.

The lecture of the fieldwork activity should be performed as: "$fieldworktype$" performed using machinery "m" on time slot "s" on a plot that has soil resistance "sr" on the planning period "t". This **does not mean** that a fieldwork activity that is soil-resistance specific, i.e., plowing using machinery "m" on time slot "s" on a plot that has soil resistance "2" (highest soil resistance) on period "t", will be returned in the fieldwork balance if the cropping activity is grown in a plot with soil resistance "1" (middle soil resistance); only the plowing -fieldwork- activities with different potential plough specifications (i.e., Anbaudreh- pflug 175 cm, or Anbaudrehpflug 210 cm) and considered of soil resistance "1" will be considered in this case. In general it is here additionally assumed that the performance of fieldwork on a plot with higher soil resistances also consumes (time) capacity from the availability of hours in lower soil resistances.

The available capacity of a single equipment that is used for performing fieldwork on lighter soil resistances also needs to consider the usage made in stronger soil resistances of the same time slot and same and lower weather levels; i.e., performing plowing activities (weather level 6, or, likewise, not very weather sensitive) with a Anbaudrehpflug 175 cm on the first half of April on a plot with soil resistance 1 will consume the available capacity of the equipment in the balances for weather level 5 with soil resistances 1 and 0 as well as the capacity provided on weather level 6 with soil resistances 2, 1 and 0.

Tractor capacities

A common feature in this model is that cropping activities require specific fieldwork types (e.g., plowing, sowing, spraying, harvesting, work residues), furthermore, each fieldwork type can be performed by choosing different equipment or machinery (fieldwork activity) and, in most cases, the performance of a fieldwork activity requires tractor power, heavier work like plowing requires more tractor power, and doing the same work with equipment of larger working width also involves higher levels of tractive power. Nevertheless, these are only minimum requirements: Work that requires 45 kW of tractive power can also be performed using 120 kW tractor but not the other way around.

To reflect this, balances have been constructed for tractive power capacities and tractor capacities. Which type of tractor, for which requirement of tractor power, at which time slot, weather level, and for which soil resistance is chosen is left to the optimization process of the modeled agent. Using the tractor to perform fieldwork in days with level 1 weather also reduces the tractor's capacity for the performing of fieldwork activities on level 6 weather. Soil resistances are also distinguished in the tractor capacities balances in the same way as the general equipment capacity implementation.

Labor capacities

The tasks of fieldwork activities require that hours of labor work be supplied. Labor constraints are distinguished by time slots, weather levels, soil resistances, and planning periods. Here we also assume that a day with weather suitable for the most weather-sensitive fieldwork is also suitable for less sensitive fieldwork; this means that using labor in days with level 1 weather also reduces the capacity of that labor for level 6 weather.

Furthermore, the soil resistances distinction is fundamental for the definition of the available time in which fieldwork is performed. Here we make the assumption that the performance of fieldwork on a plot with higher soil resistances also consumes capacity from the availability of hours in lower soil resistances.

In our modeling system, labor hours can be supplied either by the household's own labor capacity or by hiring permanent workers. We assume that household labor can provide more hours per day than hired labor, and both numbers are subject to uncertainty analysis. We provide one unit of household labor (male farmer) for all the simulations.

Crop sequence compatibility

This model was explicitly designed to simulate shifts in the dates in which fieldwork activities should be conducted. The definition of the optimal dates in which fieldwork should be performed (i.e., "...harvest should be best performed on day 250 of the year, given that the crop has achieved certain growth and development characteristics") is informed either by external information provided by the modeler in a pre-defined table or informed by an external crop growth model which is coupled with MPMAS. In the case where an external crop growth model provides the mentioned information, the specific date in which fieldwork of crop A should be performed can enter in conflict with the date in which other fieldwork for crop B should be realized: for example, due to climate change scenarios considered in the crop growth model, it has resulted that the harvesting pf crop B has delayed and the sowing of crop A should be performed earlier; therefore there is a conflict in relation to land use. These situations force the modeler to consider crop sequence compatibilities whenever potential interloping of fieldwork dates for different crops arise.

In this MPMAS model, conditions were implemented to guarantee that a crop can only be sown in a given plot of land whenever the previously grown crop has already been harvested and a minimum of "x" days gap have passed (days gap is subject of uncertainty analysis). These types of situations are relevant for rapeseed sowing operations.

Financial relationships and balance

In the model design, farm agents decide each period whether to withdraw cash (for non-farm expenditures), or to make use of the available cash to i) cover payments for long-term investment (acquisition of machinery), ii) provide for the necessary liquidity to cover payments for production (variable costs) or both, long-term investments and expenditures for short-term production.

Moreover in our model design, cash balances capture the possibility that the simulated farm agent (s) might decide to transfer cash from one period to the other to ensure the provision of the necessary liquidity to cover payments for production and future investments in the case where this decision improves its position to generate cash withdrawals in the future.

Additionally, a distinction was implemented in the cash balances, these were made to capture observed and expected prices (although not used in the simulations here presented). Whenever a farm agent sells its harvest, it does so by considering the actual observed prices in the market and actual yields achieved, the revenue gained from the selling of this products together with the cash that could have been transferred from the previous season(s) become the initial available working capital that adds to the limiting constraints that determine the possibilities of cropping and investment decisions that can be planned for the future. The future planning of cropping and investment decisions is determined by revenues and costs that depend on expected monetary values of yields and prices.

Notice that whenever a farm agent sells its harvest, it does so by considering the actual observed prices in the market, yet, our model system could also allow that the selling of the harvest of a specific crop or crops might be done with prices that are subject to contracts and can differ from the market price. Even when this is possible in our model environment, this specific feature was not implemented.

Terminal values

In this model configuration, it is assumed that the agent does not stop with farming at the end of the planning horizon but, instead, it simply does not plan beyond the planning horizon established in the scenarios evaluated. At the point of investment, we consider the full cost of the asset that is necessary to be accounted for cash expenditure, but at the end of the planning horizon, we account the remaining value of the object (cost divided by lifetime times remaining lifetime) as value occurring at the end of the planning horizon.

Policy: EU Direct Payment

The model system here described considers European Union Direct Payment regulations and ecological priority areas for greening premiums. For the modeled agent to receive a payment, it needs to comply with a series of conditions: If the modeled farm agent has less than 10 hectares, no restriction or condition applies. If the agent has between 10 and 30 hectares of arable area, it needs to grow at least two crops, none of the two can use more than 75 percent of the area. If the agent has more than 30 hectares of arable area, it is then required to grow at least three crops, from which none of the three can make more use than 75 percent of the whole arable area, and two crops together can not use more of 95 percent of the arable area. Additionally, and in terms of the priority areas for greening premiums, if the agent has more than 15 hectares it needs to reserve 5 percent for ecological purposes, this, in our model, is considered to be fallow area; the farm agent would, for this condition, necessarily have to grow fallow in order to comply with the established regulations.

The conditions above-mentioned need to be fulfilled in order for the farm agent to receive any payment from the European Union, yet these payments are distributed in dependence of the number of hectares the farm agent has; the agent receives a basis payment of 170.96 Euros per hectare and a Greening payment of 86.46 Euros per hectare. Beyond these benefits, the modeled agents receive a redistribution payment for the first 46 hectares in which the farmer receives 30 50.87 Euros per hectare for the first 30 hectares and 30.52 Euros per hectare for the next 16 hectares (values of payments are retrieved for the year 2019).

6.1.3 Inititalization and data

Agent population

All the simulations for the analysis of "Dynamic Effects of Shifts in Otimal Fieldwork Time on Land-Use and Machinery Acquisition", are performed for a single agent of 150 hectares and start at the year 2020. The initial plot history for all the 150 hectares consists of plots where the preceding land use was fallow and rapeseed has not been grown for at least three years.

Endowments

Given that the simulations performed with this model version aim to assess the sensibility of land-use patterns and optimal machinery acquisition to alternate climate change pathways, the initialization of the model system was established in terms of allowing the farm agent to perform this task. The simulated farm agent of 150 hectares was artificially endowed with a high level of liquidity (8,500,000 monetary units); this liquidity endowment serves as initial capital to acquire the necessary machinery and equipment and for input payment purposes for land-use decisions. Notice that the artificial endowment of initial capital does not affect the objective of the simulations. The model system is designed in a way that the agent maximizes the sum of the discounted value of the capital (cash) withdrawals; therefore, the mixed-integer mathematical program - that serves as the agent decision module - will always solve for the optimal choice of decision variables a given level of endowments (i.e., initial capital). If the initial cash endowment is left equal across scenarios, then the scenarios can be consitently compared in regard of the optimal decisions for land-use and machinery acquisition.

Yields

Initial yields for the crops considered in the MPMAS_XN model system were established based on a general assessment of a combination of expert opinions in the context of the research project “Regional Climate Change” (DFG - Forschergruppe 1695 Regionaler Klimawandel), statistics by Statistisches Landesamt and KTBL data. The initial values for yields can be observed in table 6.1 :

Crop	Yield (tons, wet matter)
W. Rapeseed	4
W. Wheat after W. Wheat	7
W. Wheat after others	9
W. Barley	8
S. Barley	5
S. Maize	50

Table 6.1: *Initialization of yields. Tons of wet matter*

Prices

Prices were taken from the contribution of Troost (2014) and are based on information of the State Institute for Agriculture, Food and Rural Areas (LEL) (for example, producer prices) and KTBL. KTBL provides a comprehensive compilation of acquisition prices of equipment and machinery, also, based on other prices for inputs, Troost (2014) estimated, by making use of price indices from “destatis” time series from 1996 to 2013. The simulations performed with the model componentn MPMAS of the model system MPMAS_XN in this doctoral thesis were, nevertheless, made with constant prices over all the simulation periods. Therefore, inflation was ruled out, and no variability arose from one simulation year to the other, this means that expected prices and effective prices are the same. With this assumption, it is possible to rule out in-time price variations that might be playing a significant role in the agent decision module.

Initial fieldwork dates

The initialization of ideal dates for dynamic field operations are established based on experimental fields in the context of the research project “Regional Climate Change” (DFG - Forschergruppe 1695 Regionaler Klimawandel) and on test simulations performed with the crop growth model XN. An overview of the days of the year corresponding to the ideal dates for the dynamic field operations can be observed in the table 6.2:

Fieldwork	W.Rapeseed	W.Wheat	W.Barley	S.Barley	S.Maize
Sow	239	270	259	84	118
Harvest	225	235	210	223	275
Fert. 0	241	78	78	90	117
Fert. 1	78	140	140	-	147
Fert. 2	110	158	-	-	-
Sow C.	-	-	-	242	242

Table 6.2: *Days of the year corresponding to the ideal dates for the dynamic field operations. Fert. (Fertilization), Sow C. (Sowing of cover crop)*

6.1.4 Uncertainty Analysis

We conducted uncertainty analysis on the result of the simulations to achieve the robustness of our results and evaluate them on their basis. Troost and Berger (2015) and Helton et al. (2006) argue that uncertainty analyzes is essential to assess the degree to which the findings are robust in regard to the uncertainty associated with the model inputs (e.g., parameters and exogenous variables introduced)

The ground for quantifying the uncertainty of inputs is based on the establishment of a range of potential values of the uncertain inputs considered in the structure of the submodel component MPMAS of the MPMAS_XN model system. We design and perform a global uncertainty, where we repeatedly run the simulation model across representative sample points of the potential combination of parameters. In order to define the sample of parameter combinations, we employed the Sobol sequence, which is a quasi-random sampling that has a fast converge rate and ensures proper coverage of parameter space (Tarantola et al. 2012). The optimization runs were realized for 50 repetition points of the Sobol's sample. The common uncertainty factors across all the scenarios are shown in the table 6.3.

Figures 6.2, 6.3, 6.4, and 6.5 show the convergence of the accumulated area of different crops across the 25 simulated periods.

Mpmasql4 Model Parameter	**Description**	**Uncertainty Range**
d-Rate	Factor that controls the discount rate (time preference)	0.02-0.08
Penalty area deviation	Coefficient that penalizes strong deviations across planning periods	1-3
Machinery Working Hour Limit per Day	Defines the maximum working hour limit per day for machinery and equipment	16-22
Household Working Hour Limit per Day	Defines the maximum working hour limit per day for household labor	8-16
Hired Labor Working Hour Limit per Day	Defines the maximum working hour limit per day for hired worker	8-14
Price coefficients (crops, fuel, fertilizer)	Coefficients that control the prices of expected and effective prices of production inputs and outputs	0.8-1.2
Wage Permanent Worker	Wage of hired permanent worker per year	20,000-30,000
Machine price control	Coefficient that affects the acquisition price of the machinery and equipment	0.9-1.1

Table 6.3: *Uncertainty factors common for all the scenarios in long-term simulations of the submodel MPMAS of the model system MPMAS_XN*

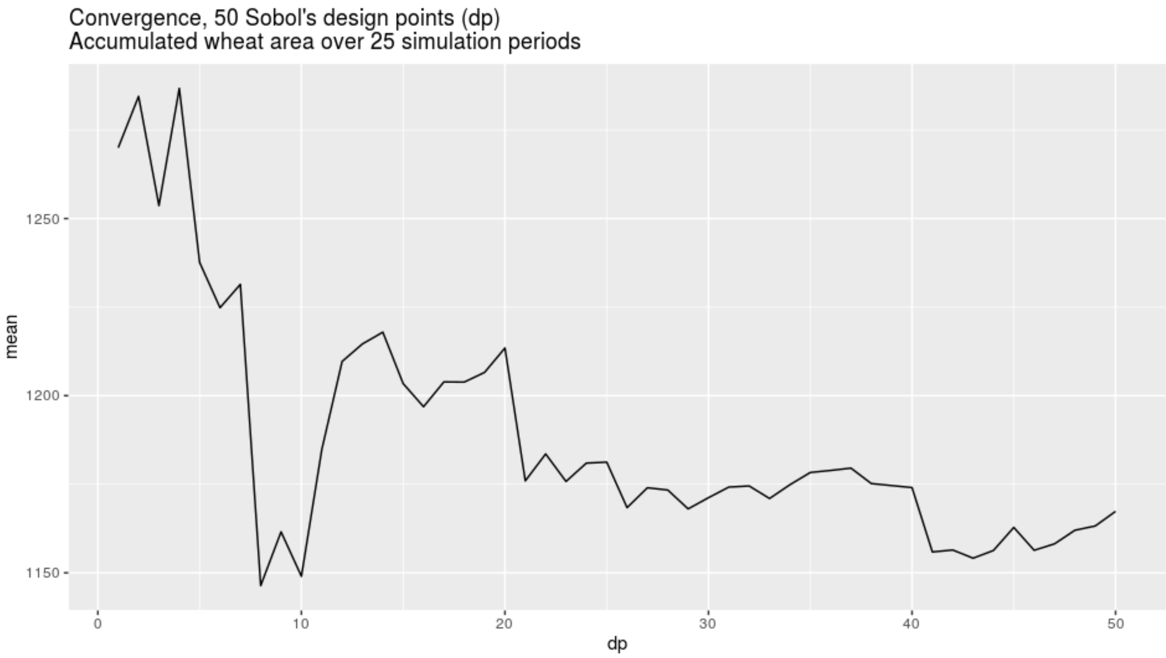

Figure 6.2: *Convergence of accumulated wheat area in baseline simulations over 50 design points of the Sobol's sequence.*

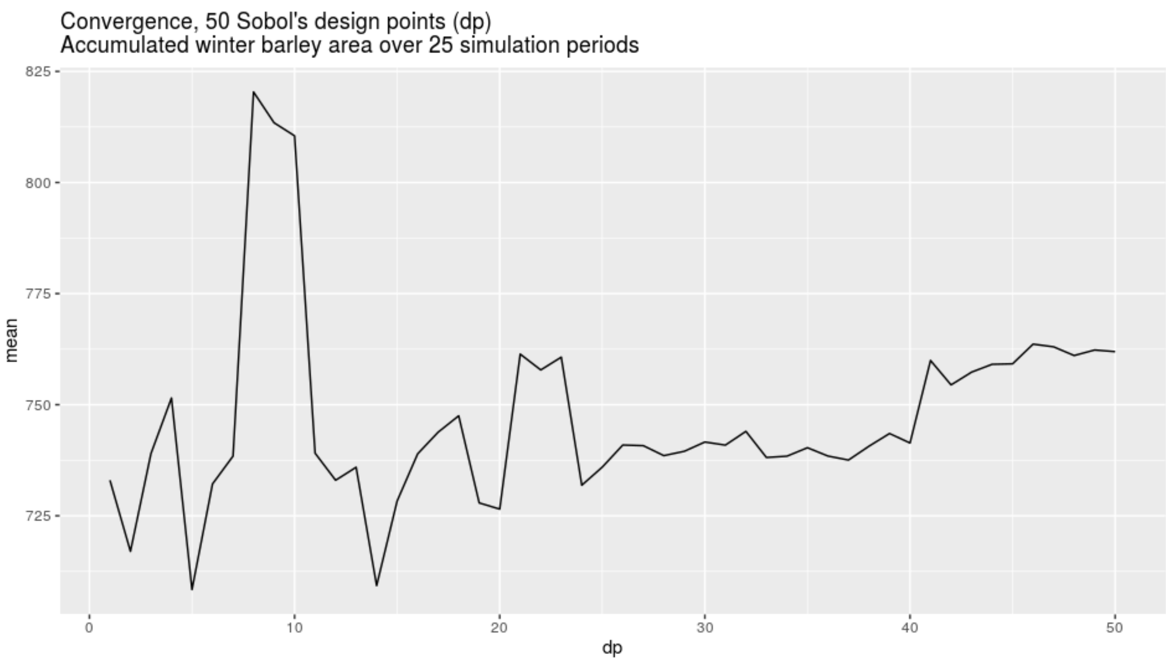

Figure 6.3: *Convergence of accumulated barley area in baseline simulations over 50 design points of the Sobol's sequence.*

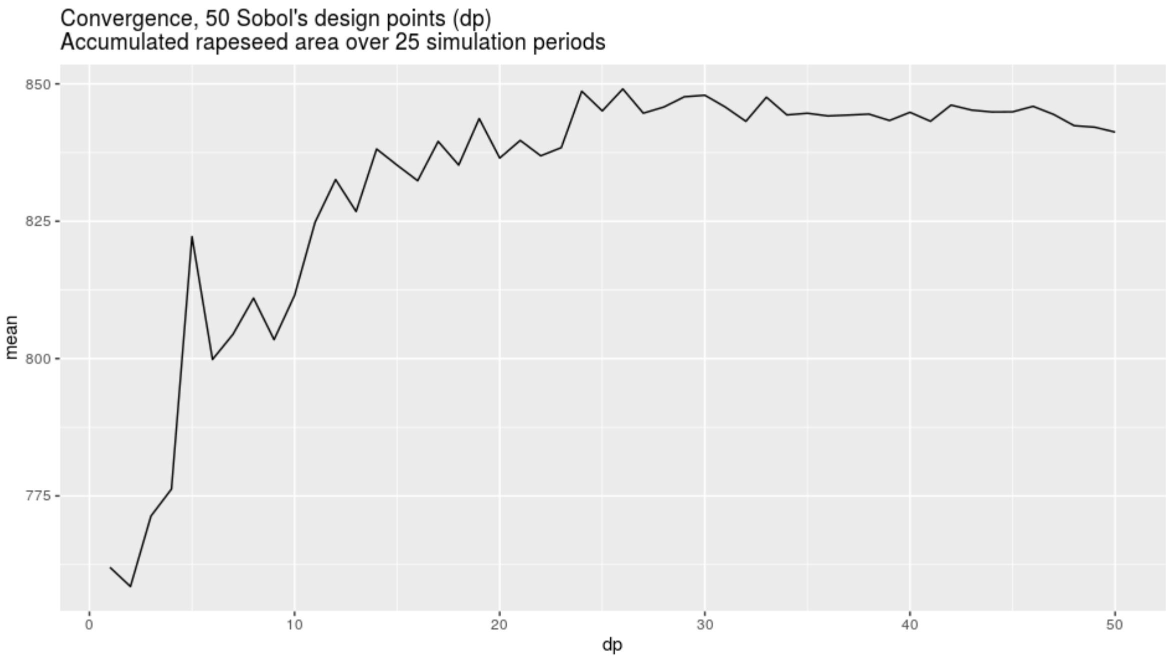

Figure 6.4: *Convergence of accumulated rapeseed area in baseline simulations over 50 design points of the Sobol's sequence.*

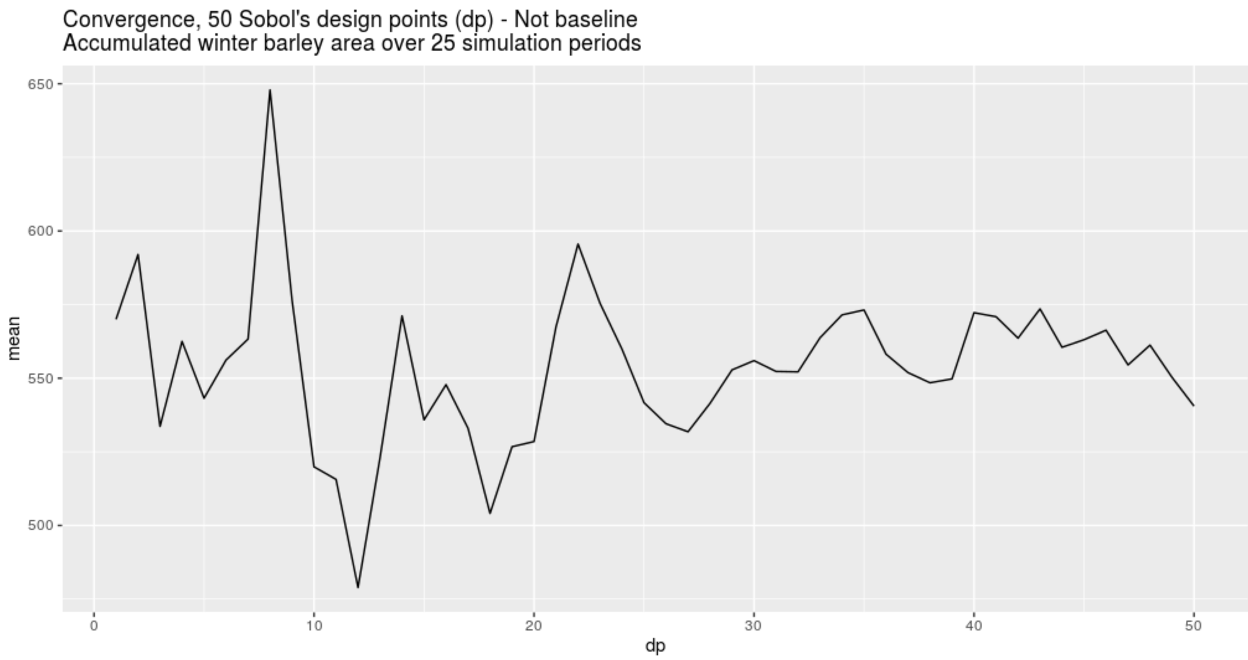

Figure 6.5: *Convergence of accumulated barley area in sceneario with long rapeseed after wheat day-gap (lower maize selling limit). Simulations over 50 design points of the Sobol's sequence.*

6.2 MPMAS optimization model for "Economies of size in farm mechanization"

In the following subsections the structure of the MPMAS model used for the subchapter: "Economies of size in farm mechanization" is provided.

6.2.1 Financial Balances

In the current model configuration, a cash balance accounts for cash expenditures and revenues in each year over the planning horizon. At the start of the period, cash is spent when investing in new machinery or equipment, for fees of owned machinery, for buying fuel, hiring labor, hiring fieldwork services from service providers, or paying debt service for any loan taken. We abstract here from different financing options and assume that one-year loans with fixed interest rate can be obtained and extended at any time without collateral. Cash inflow consists of money earned from crop production, received farm support or loans taken. Money that is not needed in a given year can be deposited off-farm earning a yearly interest. Farm return to household labor and land is accounted by balancing benefits (revenue from crop production, interests from bank deposits and direct payments) and costs (machinery yearly acquisition costs, debt service for a loan taken, machinery fees and depreciation, debt service, fuel cost, wages and cost of fieldwork services that are hired). The decision problem's assumed objective function is to maximize the discounted final wealth at the end of the planning horizon of ten years. The final wealth consists of the accumulated cash earnings from crop production, the residual value of machinery and equipment owned at the end of the planning horizon, and as a negative component, the remaining debt at the end of the planning horizon.

6.2.2 Crop choice and plot configuration

For the present analysis, the choice of crop areas is not left to the optimization process, but a typical crop rotation has been pre-specified consisting of winter rapeseed, winter wheat, and winter barley, each covering 1/3 of the production area in each year and produced in a conventional low tillage system with high yield expectations. Our model is run to obtain an optimal machinery choice for this crop rotation at different farm sizes. We assume an average plot size of 5 hectares, average plot-to-farm distance of 5 km, and medium-heavy soil (medium tillage resistance).

6.2.3 Field operations

Each crop management plan requires certain types of field operations at specific times of the season. This fieldwork demand can be satisfied selecting from predefined fieldwork activities, which represent doing a specific type of field operation with a certain equipment combination (e.g., sowing with a 2.0-meter sowing machine and a 120 kW tractor or sowing with a 4.0-meter sowing machine and a 233 kW tractor). Fieldwork activities exhibit different per-ha time demands, tractive power requirements, and fuel consumption depending on plot size, farm-to-plot distance, tillage resistance of the soil, and input quantity to be applied, resp. yield quantity to be harvested. It is left to the optimization algorithm of our MIP model to select the optimal, i.e., cost-efficient, machinery combination for the evaluated farm sizes.

The working width of all machinery operated in standing crop (mostly plant protection and fertilization) needs to be compatible with the driving lane distance selected for a plot in a specific season. Each fieldwork activity requires the availability of adequate equipment, labor capacity, and tractive power in order to be conducted at specific time windows. Our fieldwork calendar currently uses a time resolution of half-months. Following KTBL (2010), in each half-month, a certain number of days with suitable weather for specific weather sensitivity levels of fieldwork are expected with a specified probability of at least 60%. Fieldwork weather sensitivity levels range from 1 (very high demands on the weather) to 6 (not sensitive to weather). We assume that these periods are systematically overlapping: a day with suitable weather for the most weather-sensitive fieldwork is also suitable for less sensitive fieldwork. So, using machinery or labor in days with level 1 weather also occupies the capacity of that machinery for level 6 weather. The tractor, equipment, and labor capacities are calculated by multiplying the number of field days for each weather sensitivity level and each half-month with the units of equipment available and the maximum daily hours of use of the factor of production; equipment and tractors are assumed to have higher per-day hours of use than labor, restrictions are tighter on hired labor than for the farm manager's own labor.

6.2.4 Machinery and equipment

In our model configuration, we consider several alternatives for machinery and equipment acquisition. Detailed information on purchase costs, lifetime, life use, and fees of the machinery and equipment is obtained from KTBL. For example, options for combine harvesters can be acquired at capacities that range from 125 kW to 300 kW; available tractor capacities can additionally be acquired at a range between 37 kW and 233 kW and sizes for available seeding equipment range between 2 meters and 9 meters. As an alternative to the acquisition of combine harvesters, we further consider that crop harvesting services can be hired at a fixed per-ha rate (independent of volume ordered) up to a limit defined by the availability of fieldwork time at a specific half month and weather sensitivity level.

6.2.5 Labor

In our optimizations, we only consider the farm manager's own labor and no further family labor. In addition, the model permits the employment of permanent (= full year) employees on full-time, three quarter, half-time, or a quarter-time basis. Total days to be worked per year can be freely shifted between months as long as the daily maximum labor limit for hired workers is not surpassed. We allow more extended workdays for the farm manager compared with hired labor.

6.2.6 Uncertainty Analysis

In order to achieve the robustness of our results, we perform a full uncertainty design and analyze our results on its basis. Troost and Berger (2015) and Helton et al. (2006) argue on the necessity of performing uncertainty analysis in order to determine the extent to which the results and conclusions of simulations are reliable with respect to the uncertainty associated with model inputs (e.g., parameters and exogenous variables).

The foundation for quantifying the uncertainty of inputs is based on the establishment of a range of potential values of the uncertain inputs. We design and perform a global uncertainty, where we repeatedly run the optimization model across representative sample points of the potential combination of parameters. In order to define the sample of parameter combinations, we employed the Sobol sequence, which is a quasi-random sampling that has a fast converge rate and ensures proper coverage of parameter space (Tarantola et al. 2012). The optimization runs were realized for 150 repetition points of the Sobol's sample, and each of the climatic scenarios (KTBL region 4 and 7) was run using the same Sobol's sequence of parameters in order to detach the scenario effect from the variation in the uncertain parameters. The table 6.4 presents the parameters considered for the design of the uncertainity sample.

The figures 6.6 and 6.7 show the convergence of the return to own labor and land for two farm agent managing different farm sizes. At 150 design points we can safely state the achievement of convergence.

Mpmasql4 Model Parameter	**Description**	**Uncertainty Range**
Machine Working Hour Limit per Day	Defines the maximum working hour limit per day for machinery and equipment	16-22
Household Working Hour Limit per Day	Defines the maximum working hour limit per day for household labor	8-16
Hired labor working Hour Limit per Day	Defines the maximum working hour limit per day for hired worker	8-14
Terminal Value Coefficient	Parameter that controls how much of the book value of machinery should be considered in the optimization	0.8-0.98
Wage Permanent Worker	Wage of hired permanent worker per year	20,000-30,000
v-Fuel	Factor that controls the fuel cost	0.8-1.2
Borrow Rate	Interest rate of the borrowed capital	0.03-0.09
Raps CostHire	Hiring monetary rate per hectare for rapeseed harvest	98-182
Non Raps CostHire	Hiring monetary rate per hectare for non-rape harvest	77-143
Interest Rate Short Term Deposit	Interest rate for one year deposits	0.003-0.008
v-DCost	Factor that controls the direct cost of production	0.85-1.15
d-Rate	Factor that controls the discount rate (time preference)	0.02-0.07
duration Credit	Duration of plan of borrowed cash	1-8
control Hire	Factor that controls the limit for hiring harvest services	1-3

Table 6.4: *Ranges of uncertainty parameters for the optimization model for analysis of economies of size in farm mechanization*

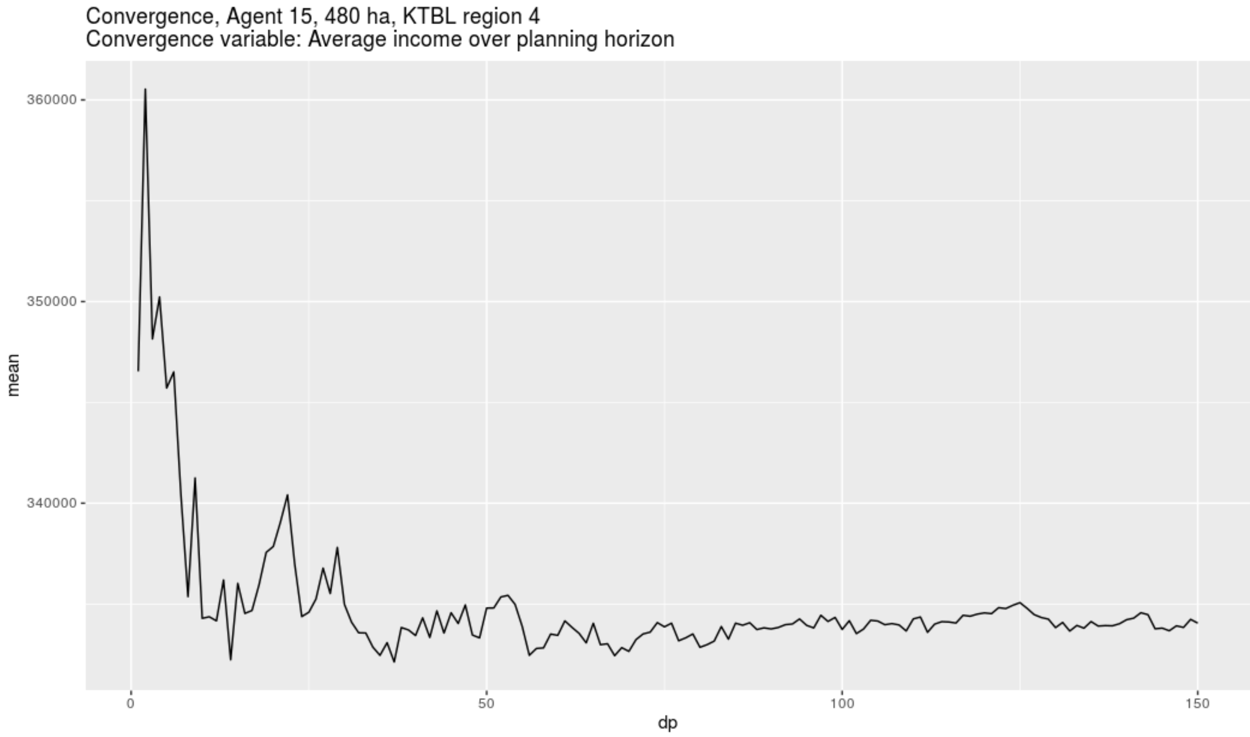

Figure 6.6: *Convergence of income (only return to own labor and land) over 150 design points of uncertainty analysis*

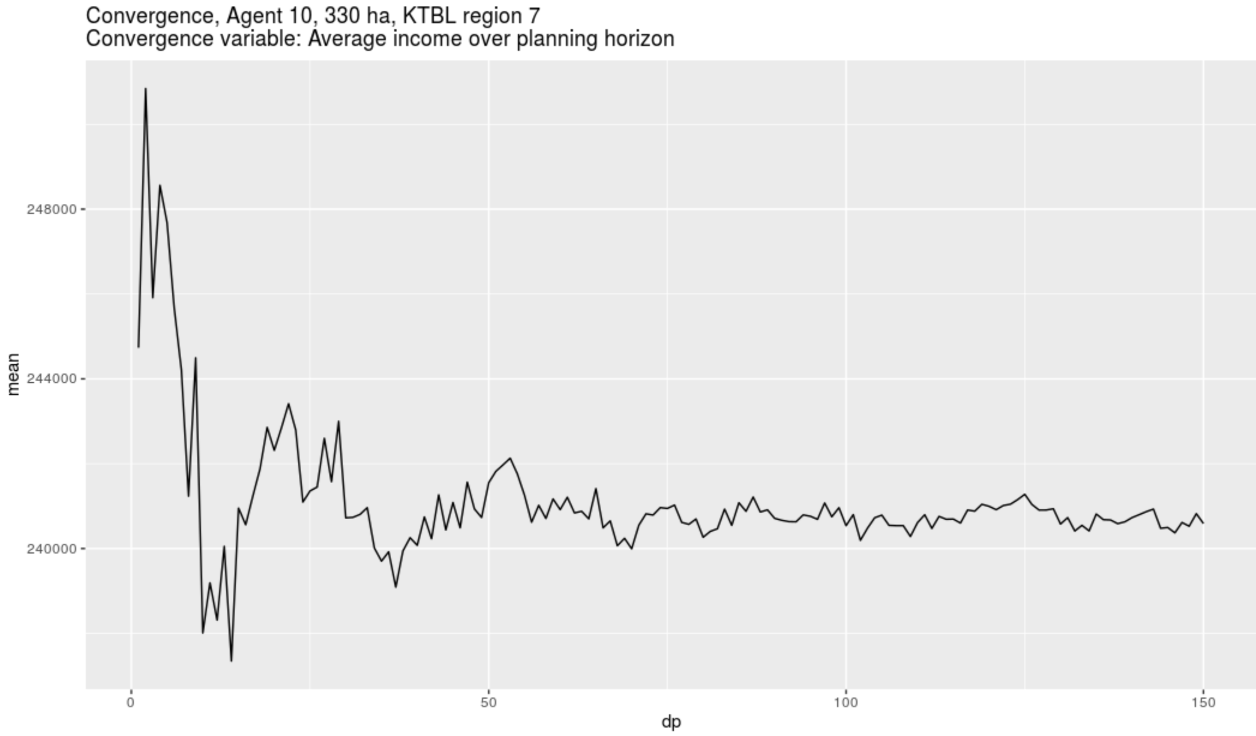

Figure 6.7: *Convergence of income (only return to own labor and land) over 150 design points of uncertainty analysis*

Annexes

6.3 Annexes for: "Dynamic effects of shifts in fieldwork time on land-use and machinery acquisition"

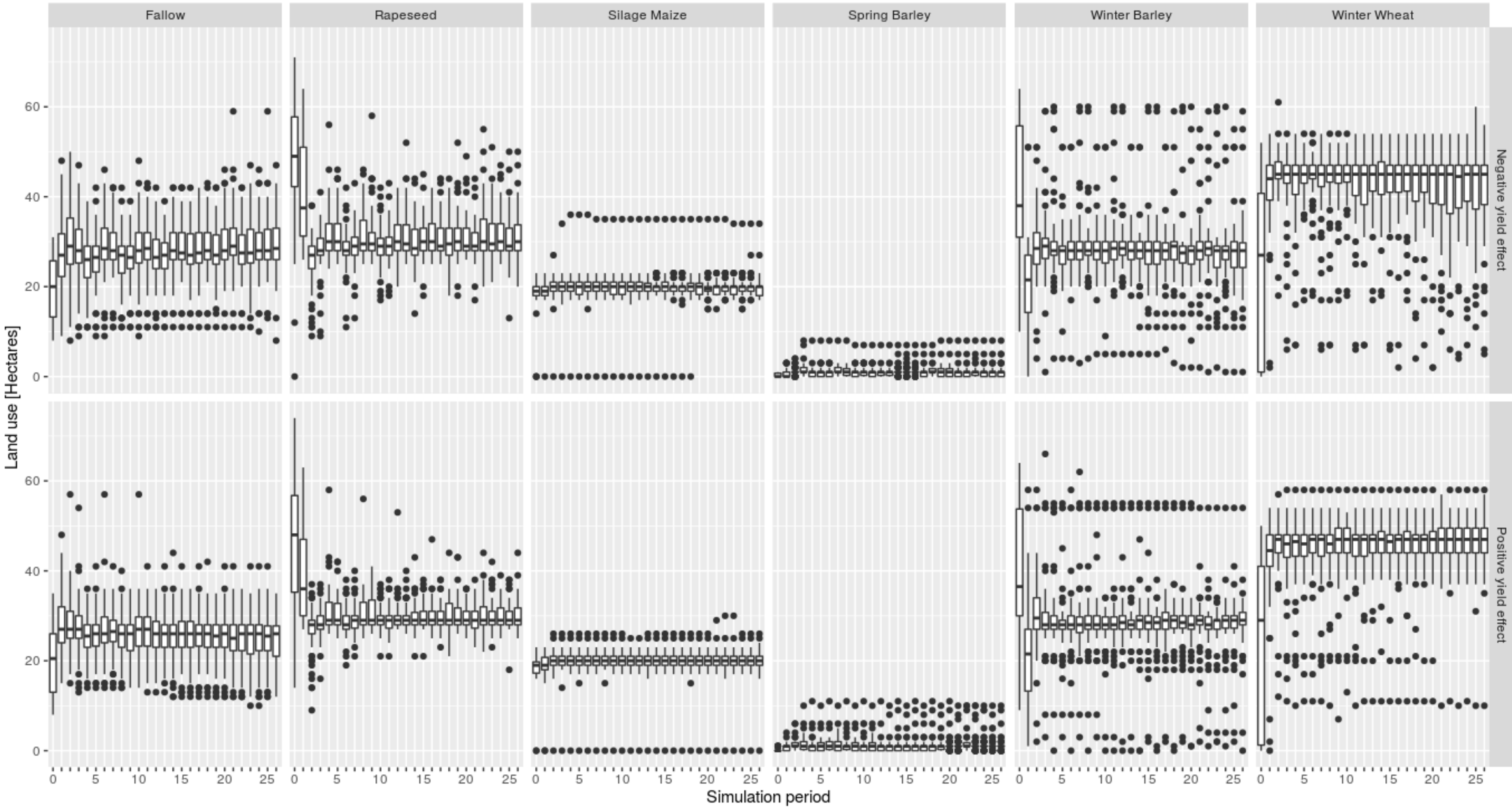

Figure 6.8: *Simulated land use over 25 years. Scenario 1 "Positive yield effect" and scenario 2 "Negative yield effect". Results over 50 design points of the Sobol's sequence*

6.4 Annexes for: "Economies of Size in Farm Mechanization"

6.4.1 Example for reorganization of fieldwork demand as a result of changing climate zones

The following example shows a detailed example of one optimization problem that belongs to one uncertainty point of the Sobol's sequence (other optimizaton problems of different design points of the Sobol's sequence were also examined, and similar results were observed). The detailed examination reveals that a higher value machinery acquisition can result together with a higher demand for labor in the scenario with tighter time windows, KTBL climate zone 4, compared to the scenario with looser time windows.

The results are shown for an optimization problem of a 540-hectare size in both climate zones (4 and 7). The climate zone 4 shows less available days for field operations than the zone 7. This condition in climate zone 4 requires equipment with higher efficiency than climate zone 7: For instance, a larger seeding equipment is required. The 2.5 meters-wide seeding equipment in climate zone 7 is updated towards a three meters-wide seeding equipment in the context of climatic region four. Also, a higher-capacity phytosanitary syringe is required from a 1,500 liters tank in the context of climate zone 7 to a 3,000 liters tank in climate zone 4. These differences in equipment acquisition result in an overall initial investment cost in optimal machinery portfolio of 769.6 thousand Euros in the zone 4 and 733.4 in the zone 7.

In the climate zone 7, the optimization problem shows that the seeding operations for rapeseed (service 179.82 hectares, or one-third of the arable land according to the assumed crop rotation) should be performed with a 2.5 meters-wide seeding equipment. With an efficiency of service of 1.06 hectares per hour, employing the fieldwork activity that makes use of a 2.5 meters-wide seeding implement for rapeseed is feasible in the timeslot where rapeseed is sown; the supply of time available at this half month is higher than the demand of time associated with the fieldwork activity for rapeseed sowing with a 2.5 meters-wide seeding implement.

In the scenario with less available time for fieldwork operations (climate zone 4), the use of a 2.5 meters-wide seeding implement for rapeseed sowing would not be feasible. At the climate zone 4, the supply of available time on the specific time window and fieldwork sensitivity level for sowing rapeseed is lower than in climatic region seven. The optimization problem suggests that the rapeseed seeding fieldwork operation should be best performed with a 3 meters-wide seeding implement instead of a 2.5 meters-wide. A similar result is found for the performance of plant protetction operations with the phytosanitary syringe.

Moreover, the optimization problems for zones 4 and 7 show that other fieldwork operations can be best performed by combining two activities, for example, sowing a part of the area to be serviced with a small implement (and the associated tractor capacity, e.g., 67 kW), and sowing the rest of the area with a larger implement and the associated larger tractor capacity (e.g., 83 kW). The reason for this combination of fieldwork activities is that the whole-farm multiperiod optimization problem recognizes that at a specific half-month, several field operations can be performed, and all of them require tractor and labor capacities together with their particular implements.

Table 6.5 shows the demand for tractor time in the second half of September for all the acquired tractors resulting as an optimal acquisition from the optimization problem.

Climatic region 4					
Half-Month	**Tractor 200 kW Demand (hrs) (1)**	**Tractor 67 kW Demand (hrs) (2)**	**Tractor 83 kW Demand (hrs) (3)**	**Accumulated Time demand (1+2+3) (hrs)**	**Time supply (hrs, weather sens. 5 for 1 tractor)**
Aug1	0	160.04	60.46	220.5	189
Sep2	215.93	51.13	28.86	295.9	231
Oct2	5.08	168	94.70	267.78	168
Climatic region 7					
Half-Month	**Tractor 200 kW Demand (hrs) (1)**	**Tractor 67 kW Demand (hrs) (2)**	**Tractor 83 kW Demand (hrs) (3)**	**Accumulated Time demand (1+2+3) (hrs)**	**Time supply (hrs, weather sens. 5 for 1 tractor)**
Aug1	0	248.15	11.90	260.05	273
Sep2	241.82	0	35.36	277.14	273
Oct2	72.74	153.53	30.66	256.93	231

Table 6.5: *Time demand and supply for tractors acquired in the optimal solution for a 540-hectares optimization problem. Result obtained for one design point of the Sobol sequence as example.*

For example, in the second half of September, there is a demand for the time of a 200 kW tractor at the level of 241.82 hours in the climatic region seven. This demand is the result of performing the following fieldwork operations (with weather sensitivity level 5) that require a 200 kW power: Second stubble (deep) cultivation (179.81 ha), seeding of winter barley with a rotary harrow and seeding implement (174.55 ha), and standard deep cultivation operations (179.81 ha).

The fieldwork plan described for climate zone 7 would not be feasible in the climatic region four without acquiring an additional tractor of 200 kW (241.82 hours demanded in climatic region seven in Sep2 versus 231 hours available in climatic region four in the same half-month). The supply of available time in climate zone 4 is lower than the demand of time resulting from the fieldwork plan described for climatic region seven to use a 200 kW tractor. The decrease in available time for fieldwork operations drives the optimization problem to perform a reorganization of fieldwork activities. In the scenario with tighter time windows, the serviced of areas for a second stubble (deep) cultivation (179.81 ha) and standard deep cultivation operations (179.81 ha) are kept as they were in climatic region seven, but the area of winter barley that is sown by employing the 200 kW tractor and a six meters-wide implement is reduced from 174.55 to 124.78 hectares, thus reducing the time preassure associated to the use of the 200 kW tractor.

The reduction in the 200 kW tractor's time demand for the sowing of winter barley in climate zone 4 means that an alternative fieldwork activity needs to be performed to complement the area to be sown. In this case, a lower capacity tractor (a 67 kW tractor servicing for 51.13 hours in Sep2, region four) is used to draft smaller equipment (three meters-wide seeding implement, which exhibits lower ha-efficiency), while resulting in an overall higher demand for work time that is reflected in a higher demand for labor time in comparison to climate region seven the second half of September.

6.4.2 Demand and excess capacity trends and courses for different types of machinery resulting from the optimization problem.

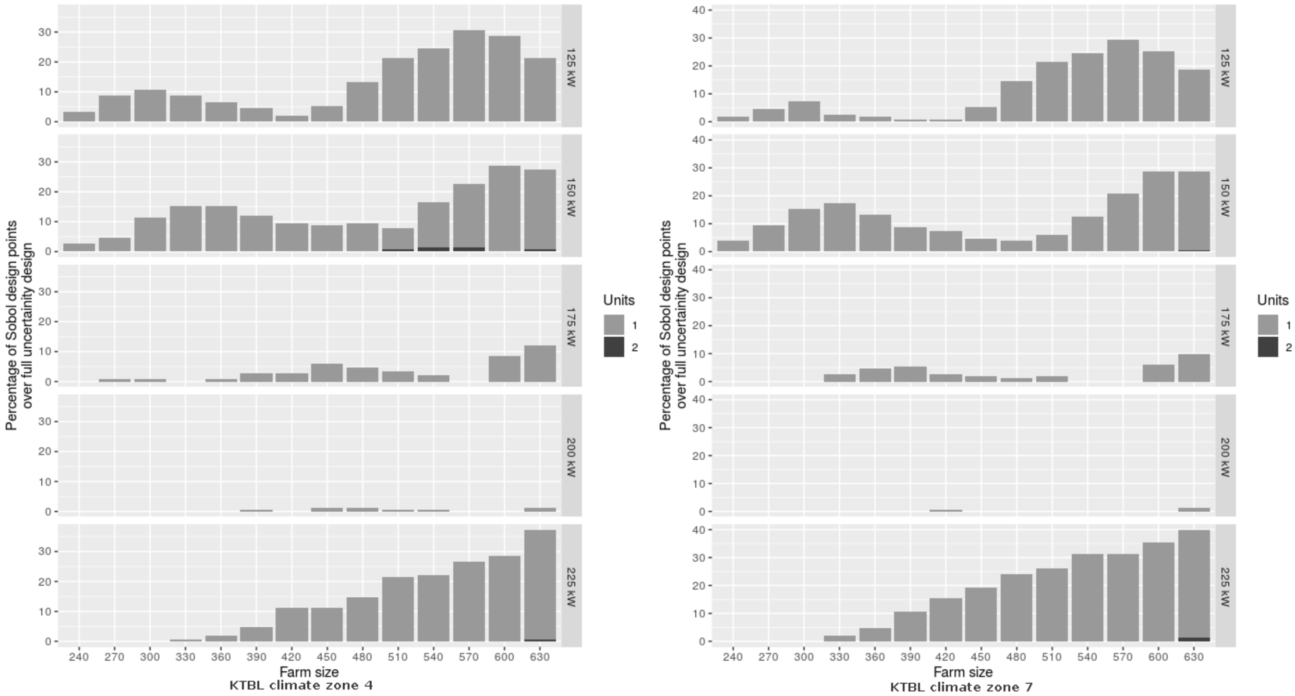

Figure 6.9: *Machinery and equipment acquisition: Combine harvester. Percentage of Sobol's design points where each machinery type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence*

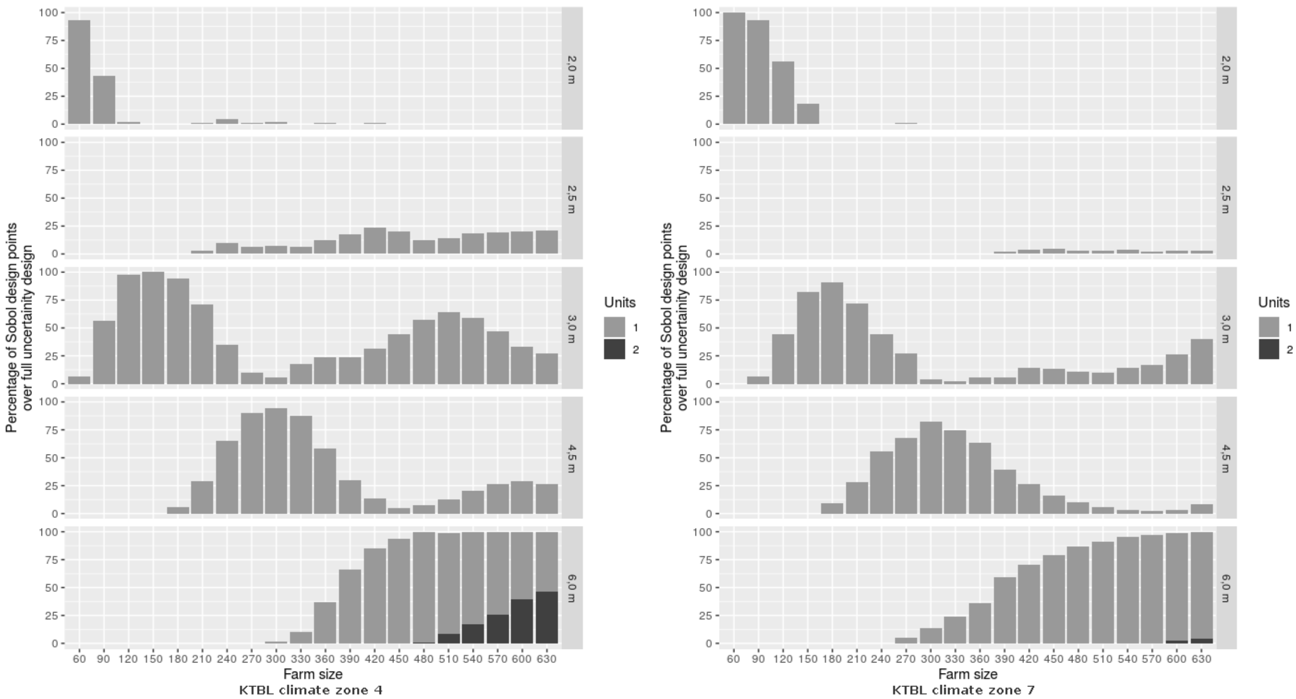

Figure 6.10: *Machinery and equipment acquisition: Cultivator. Percentage of Sobol's design points where each machinery type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence*

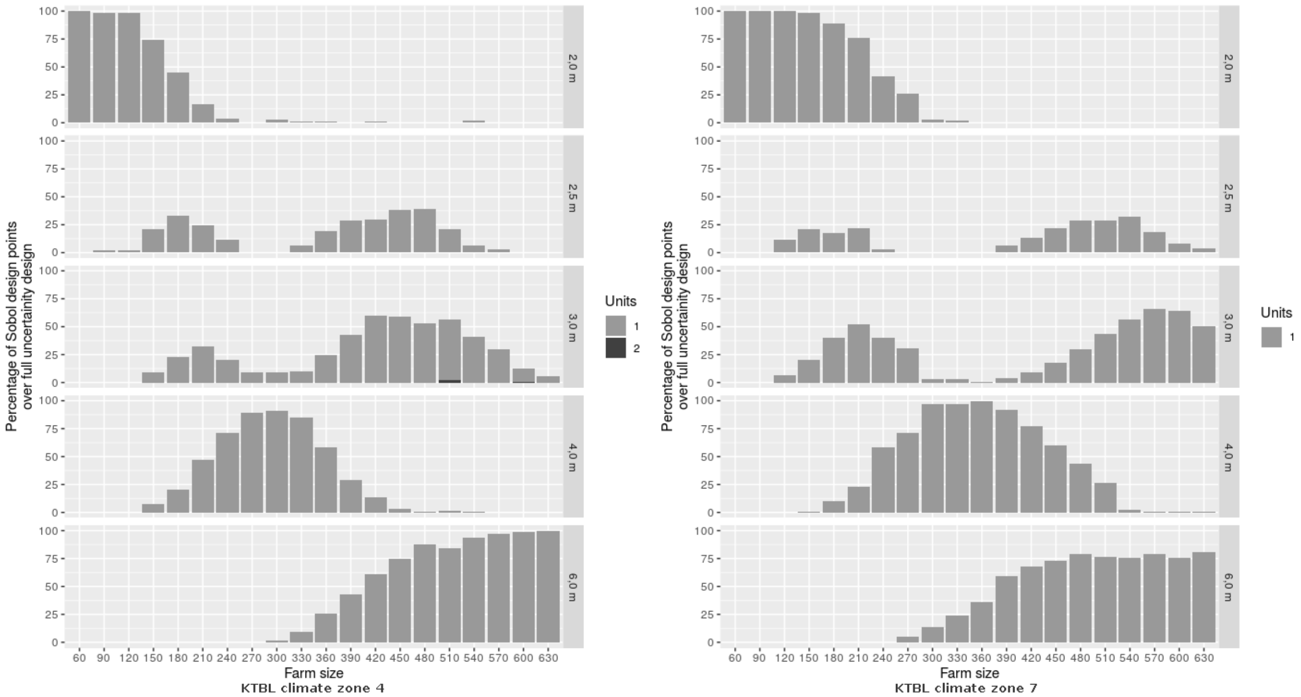

Figure 6.11: *Machinery and equipment acquisition: Rotary harrow. Percentage of Sobol's design points where each machinery type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence*

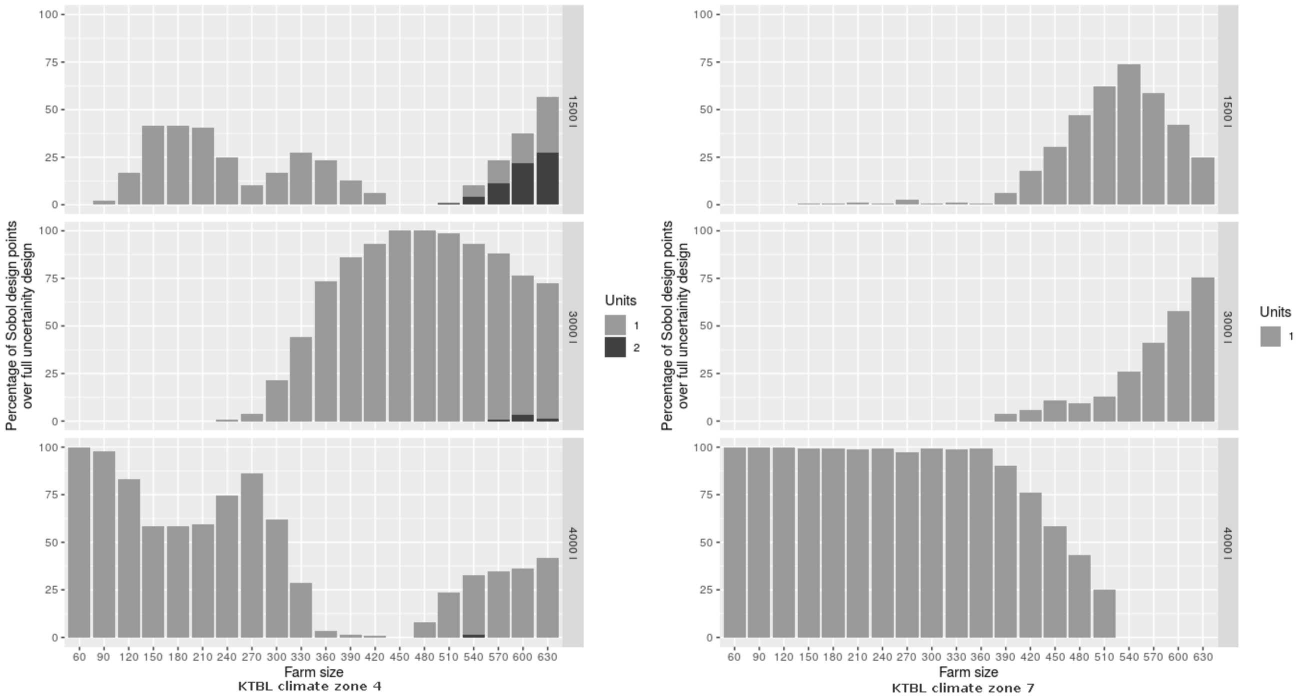

Figure 6.12: *Machinery and equipment acquisition: Crop protection sprayer. Percentage of Sobol's design points where each machinery type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence*

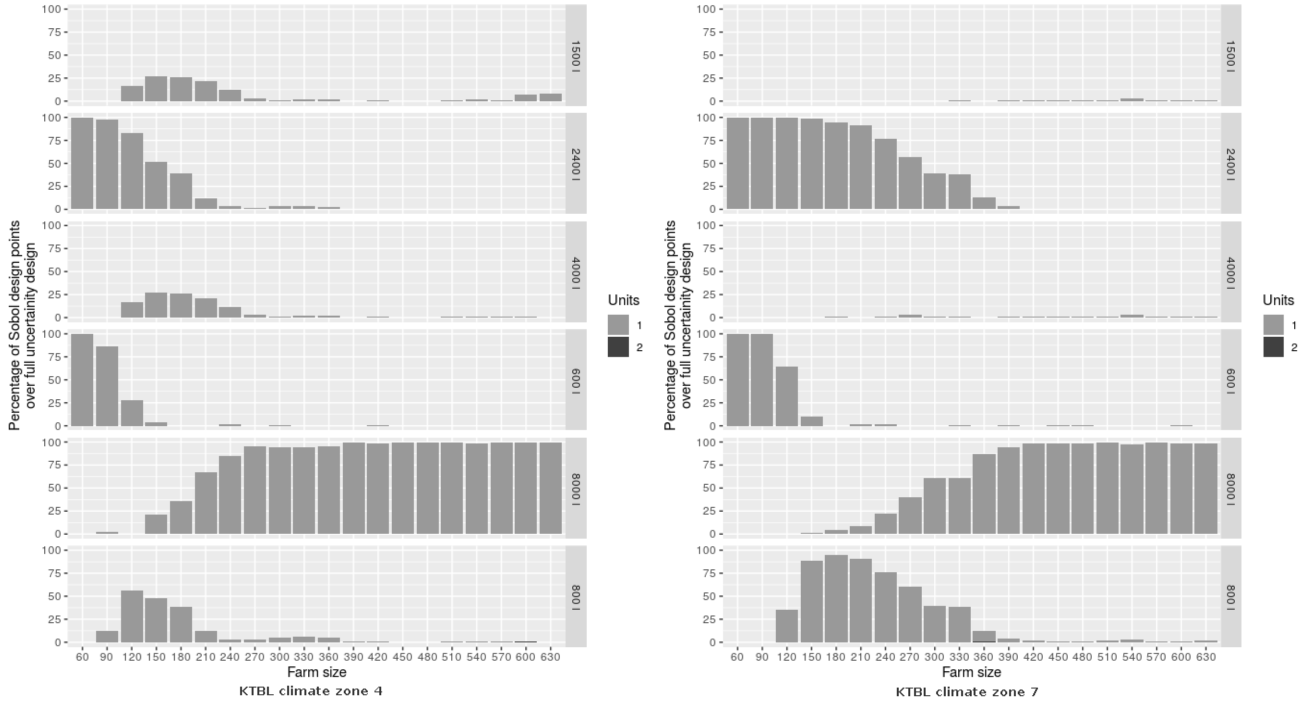

Figure 6.13: *Machinery and equipment acquisition: Centrifugal spreader. Percentage of Sobol's design points where each machinery type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence*

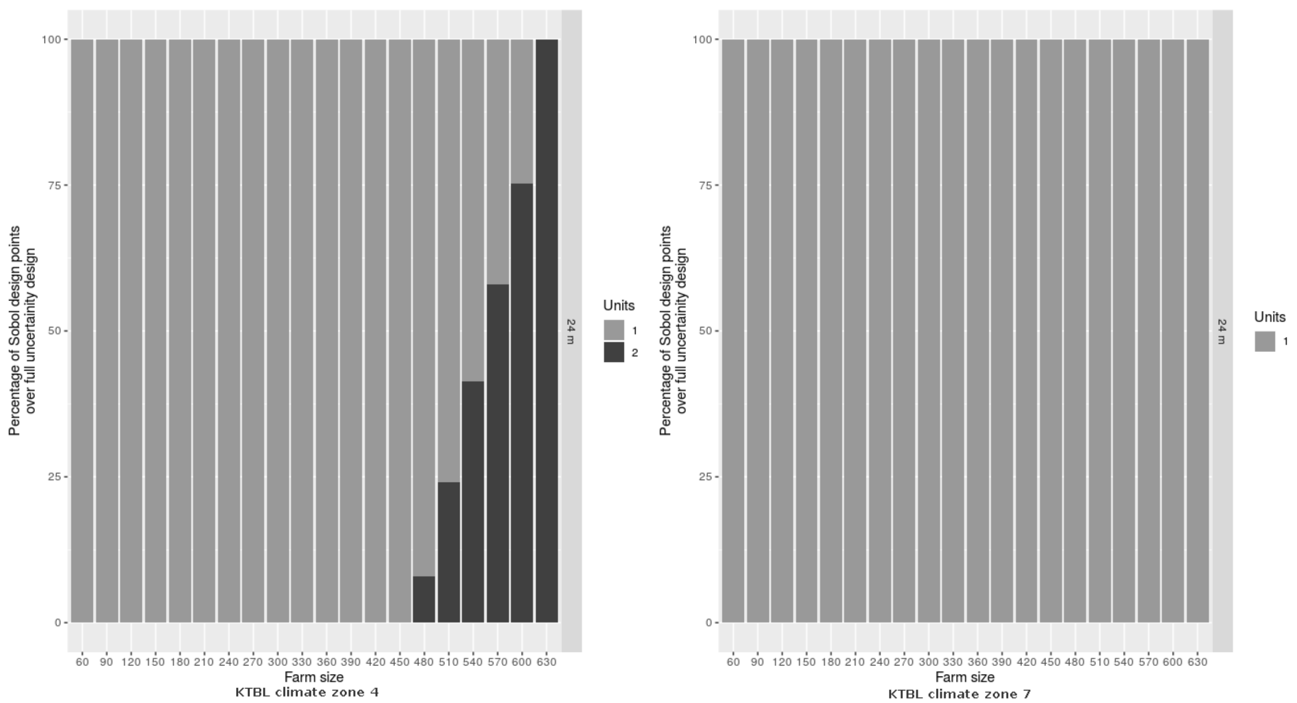

Figure 6.14: *Machinery and equipment acquisition: Spray boom. Percentage of Sobol's design points where each machinery type is demanded. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence*

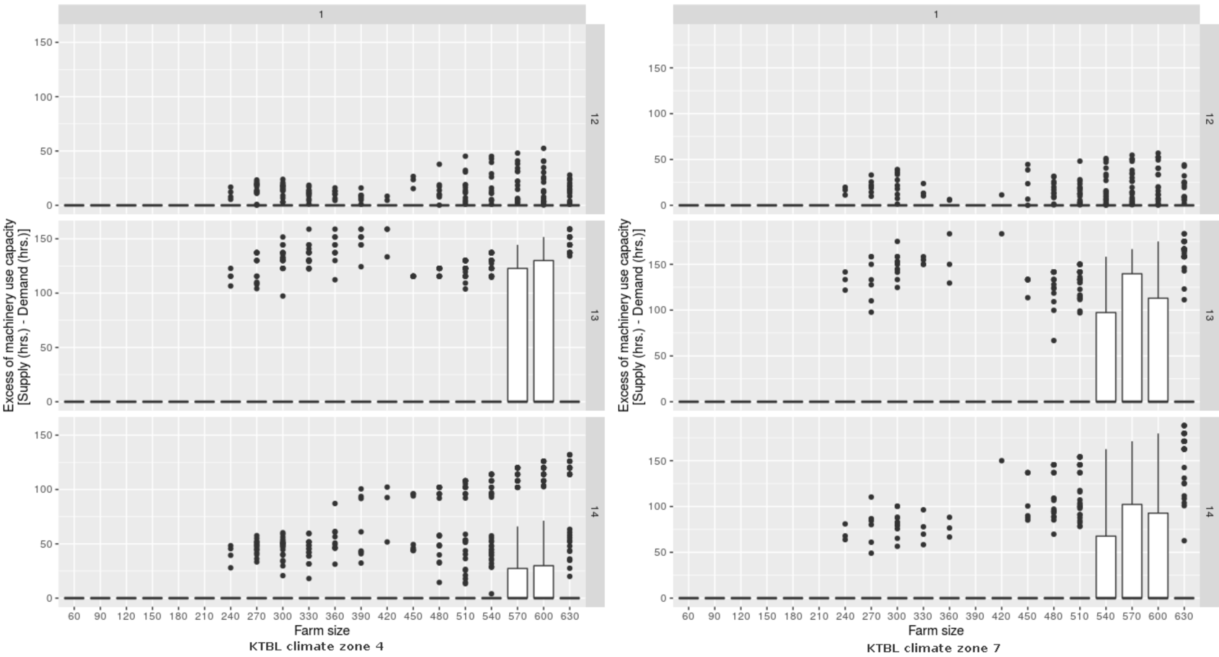

Figure 6.15: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Combined harvester 125 kW. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis). Half months: 12 (JUL1), 13 (JUL2), 14 (AUG1)*

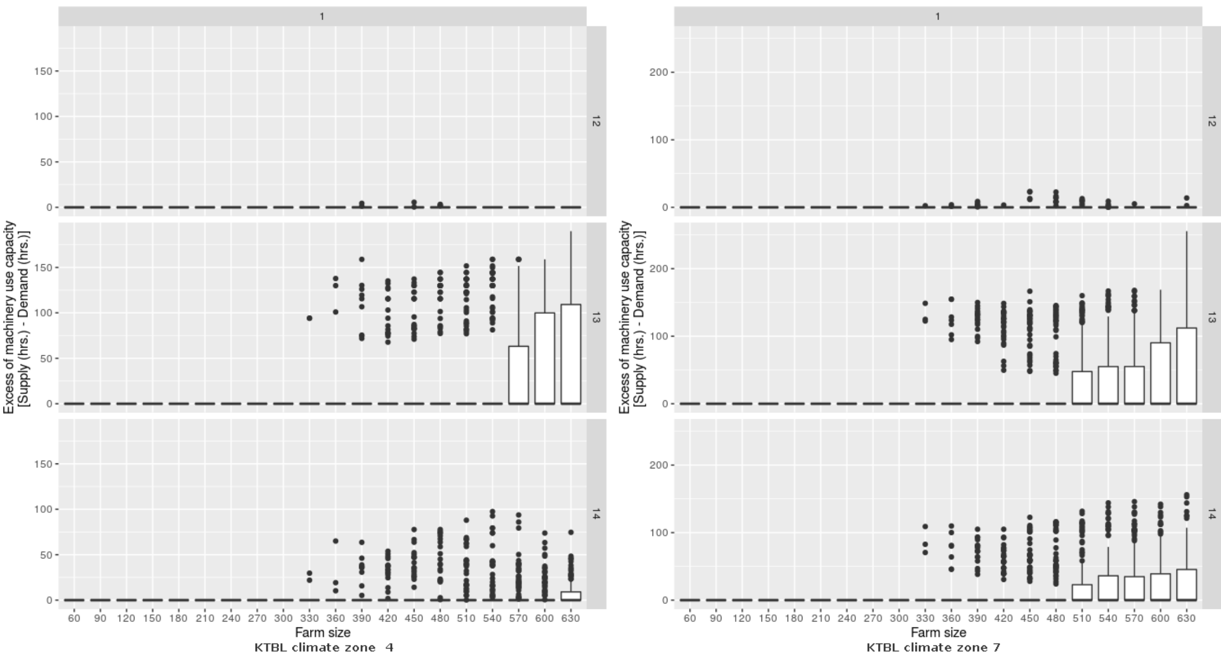

Figure 6.16: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Combined harvester 225 kW. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis). Half months: 12 (JUL1), 13 (JUL2), 14 (AUG1)*

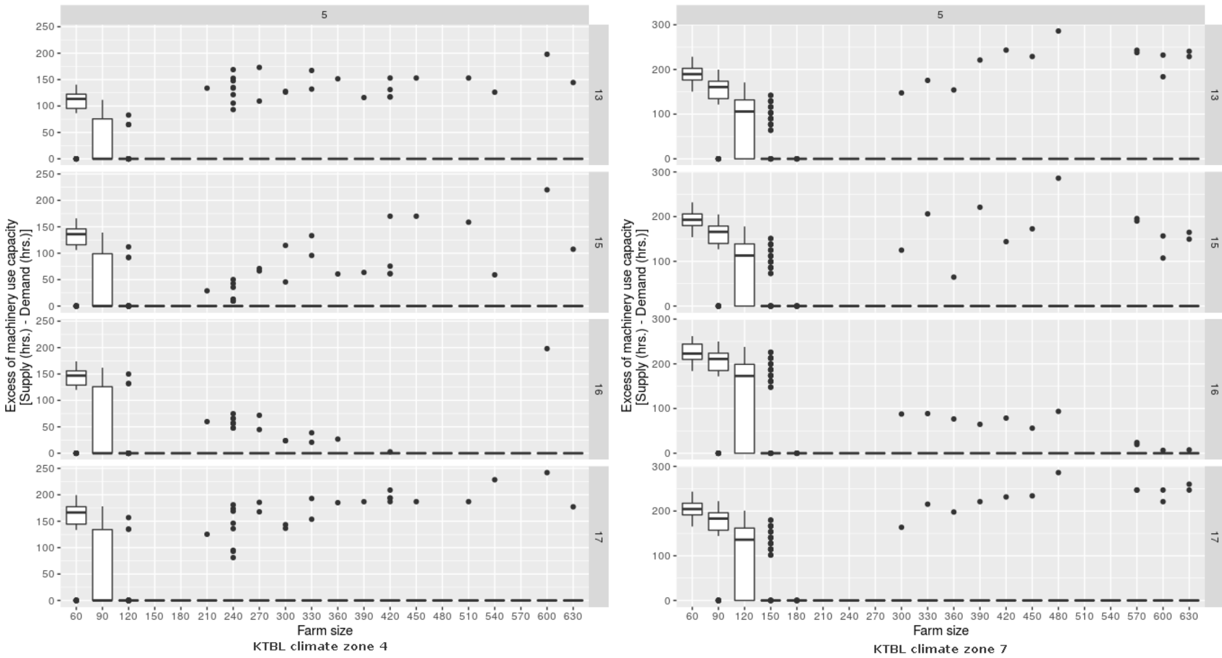

Figure 6.17: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Cultivator two-meters. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis). Half months: 13 (JUL2), 15 (AUG2), 16 (SEP1), 17 (SEP2)*

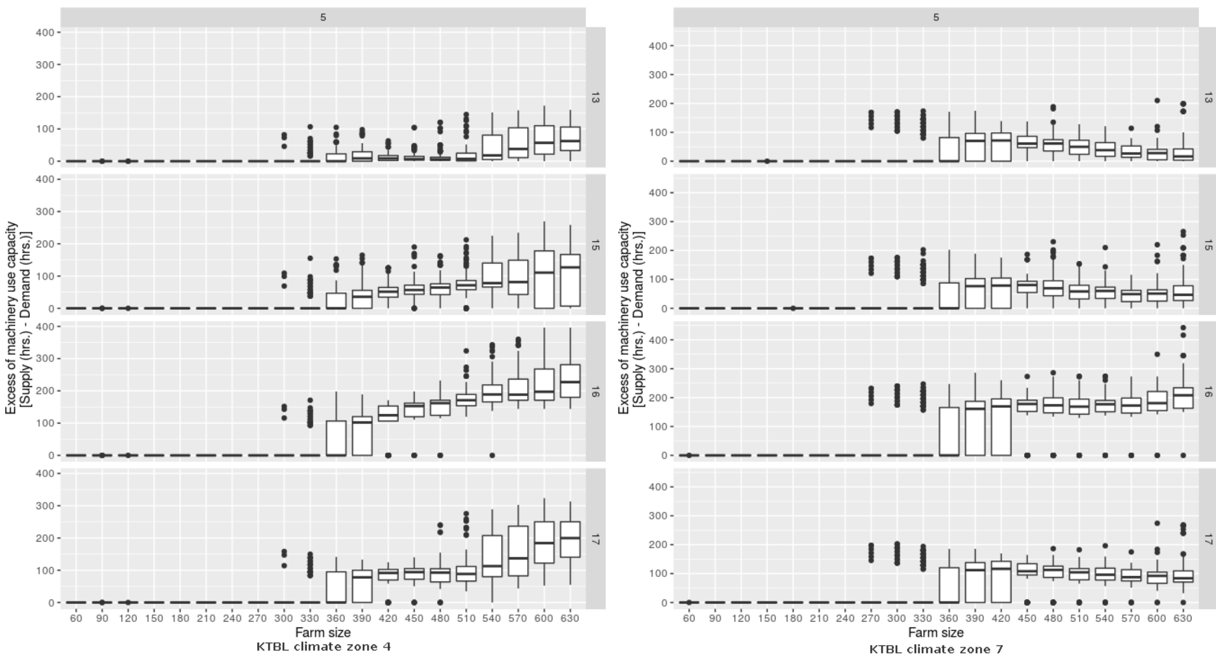

Figure 6.18: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Cultivator six-meters. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis). Half months: 13 (JUL2), 15 (AUG2), 16 (SEP1), 17 (SEP2)*

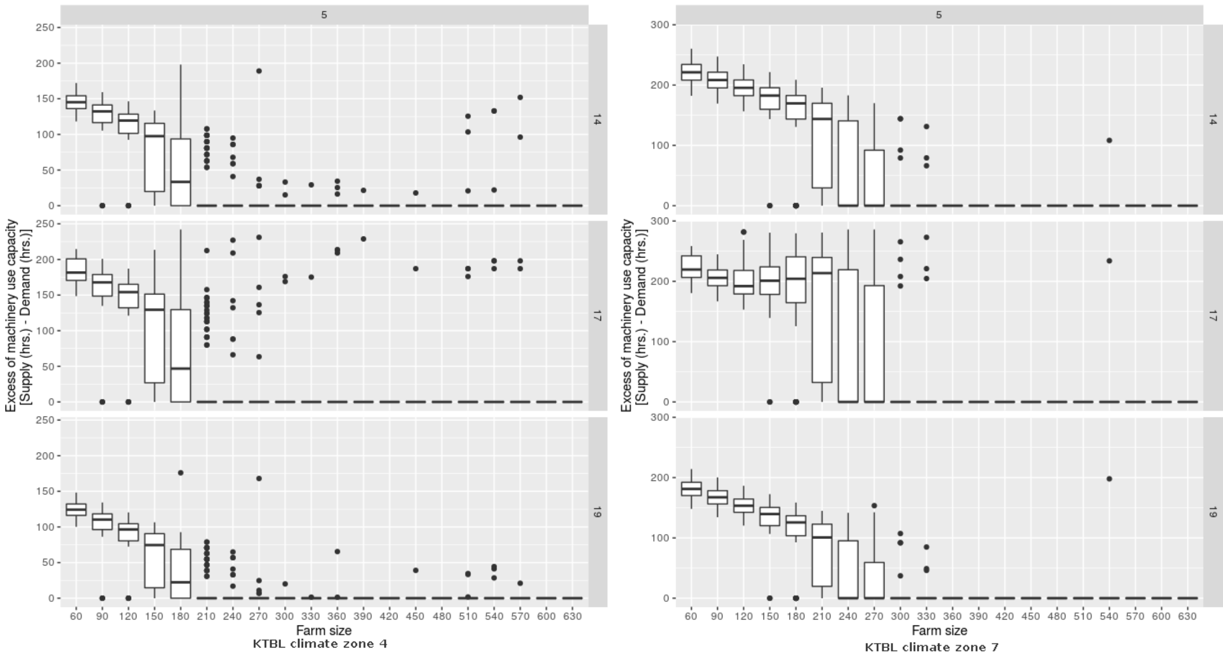

Figure 6.19: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Rotary harrow two-meters. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis). Half months: 14 (AUG1), 17 (SEP2), 19 (OKT2)*

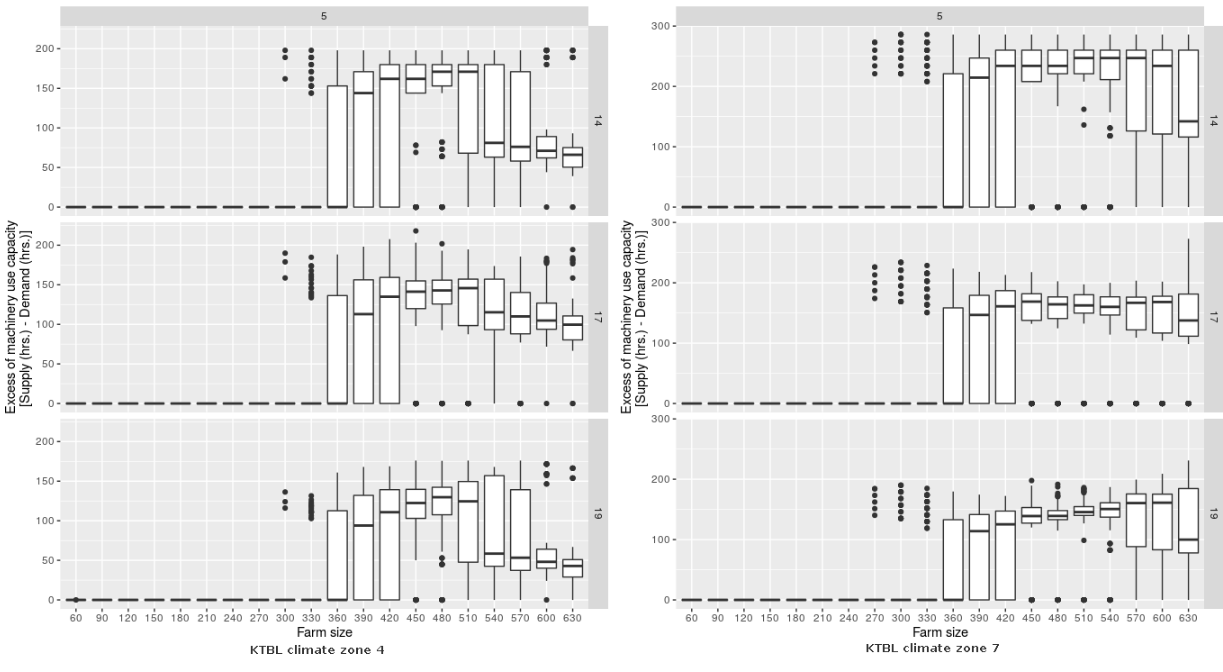

Figure 6.20: *Excess of machinery-use capacity (Supply of available hours for fieldwork minus demand of hours for fieldwork): Rotary harrow six-meters. Result shown for 150 design points of uncertainty analysis with the Sobol's sequence. Half month (vertical axis), weather level (horizontal axis) Half months: Half months: 14 (AUG1), 17 (SEP2), 19 (OKT2).*

Chapter 7

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Chapter 8

List of Abbreviations

ABM .... Agent-based models

BMEL .... Bundesministerium für Ernährung und Landwirtschaft

CSJ .... Central Swabian Jura

CAP .... Common Agricultural Policy

cm .... centimeter

ef .... Machinery efficiency

FC .... Field capacity

FDR .... Field day requirement

ha .... Hectare

IPCC .... Intergovernmental Panel on Climate Change

kW .... Kilowatt

KTBL .... Kuratorium fuer Technik und Bauwesen in der Landwirtschaft

LEL .... Landesanstalt für Landwirtschaft, Ernährung und Ländlichen Raum

LfL .... Landesanstalt für Landwirtschaft

LUCC .... Land use and Cover Change models

MAS .... Multi-agent systems

MIP .... Mixed integer mathematical programming

MP .... Mathematical programming

MPMAS ..... Mathematical Programming-based Multi-Agent Systems

NRU .... Nutrient response unit

ReKliEs ...... Regionale Klimaprojektionen Ensemble

U.S. .... United States of America

XN .... Expert N