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Social-ecological modeling for policy analysis in transformative land systems - Supporting evaluation and communication for sustainability

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Social-ecological modeling for policy analysis in transformative land systems

Supporting evaluation and communication for sustainability

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ABSTRACT

The increasing demand for food and fiber, the need for climate change mitigation and adaptation as well as for environmental protection impose severe challenges on land systems worldwide. Solutions to support the transformation towards a sustainable development of land systems are needed. One response to the multiple challenges is the introduction of policy options aimed at steering land use activities towards a bundle of societal goals. However, it is difficult to empirically foresee the effectiveness and unintended consequences of policy options prior to their deployment. A second response is environmental education because human consumption behavior, among other factors, strongly influences natural ecosystems. However, it is a non-trivial task to develop effective communication strategies for complex topics such as sustainable land management. In both cases, modeling can help to overcome the different obstacles along the way.

In this thesis, dynamic process-based social-ecological models at the individual scale are developed and analyzed to study effectiveness and unintended side effects of policy options, which promote agricultural management strategies and were intentionally designed to cope with multiple societal challenges. Two case studies of political intervention are investigated: the promotion of perennial woody crops in European agricultural landscapes for a sustainable bioeconomy and governmental supplementary feeding programs to cope with climate risks in pastoral systems in drylands. These two case studies are complemented by the development of a serious online game on sustainable land management in general that bridges the gap between land use modeling and environmental education.

Simulation results of this thesis provide insights into (i) the performance of the politically promoted agricultural management strategies in meeting various intended goals such as poverty alleviation or the maintenance of biodiversity and ecosystem services, (ii) the emergence of unintended (environmental and social) side effects such as land use conflicts, land degradation or cost explosion and (iii) the mitigation of such side effects by appropriately adjusting the design of the policy options. These insights are enabled by representing temporal as well as spatial variability in the developed models. Furthermore, different mechanistic approaches of transferability analyses based on stylized landscapes are developed and applied. They enable to check whether and in what respect policy impacts actually differ substantially between regional contexts, to identify what regional factors steer the impact and to derive indicators for grouping regions of similar policy impacts. Finally, based on a conducted survey-based evaluation and experiences from various applications, the value of the developed serious game for environmental education is revealed and discussed.

Altogether, this thesis contributes to model-based decision support for steering transformation towards the sustainable development of land systems in an appropriate way. This is done by developing appropriate social-ecological modeling approaches, by performing specific policy impact analyses in two transformative agricultural systems using these models and by providing a model-based communication tool for environmental education.

CONTENTS

1

INTRODUCTION

1.1 PROBLEM BACKGROUND

Human populations substantially influence global land use to satisfy their needs for food, fiber and energy. Today, 75% of the ice-free land shows human-induced alteration (Ellis and Ramankutty, 2008) and humans use almost 30% of global terrestrial net primary production, i.e., gain in plant biomass (Haberl et al., 2007). These shares are expected to further increase due to population growth, changing consumption patterns and, last but not least, the urgent need for climate change mitigation and thus a transition to decarbonization of the entire economy and particularly the energy system (Foley et al., 2011; WBGU, 2011). The latter causes a growing relevance of bioeconomy and renewable energies, which encompasses the production and conversion of bio-based renewable resources. Together with the other drivers and an already ongoing degradation of land, this will cause an intensification of land use conflicts between different environmental goods and services in demand as well as climate and natural resource protection (Sheppard et al., 2011; Pfau et al., 2014). Furthermore, climatic changes such as the increasing occurrence of droughts impose severe challenges in several land use contexts, for example the risk of loss of livelihood security for pastoralists in drylands (Parry et al., 2009; IPCC, 2014). Thus, one of the greatest challenges of the 21st century is meeting society's needs while reducing environmental harm caused by land use change (Godfray et al., 2010; Tilman et al., 2011; Foley et al., 2011). Solutions to organize the transformation towards a sustainable development of land systems are urgently needed.

The largest share of human appropriation of net primary production, almost 80%, is covered by the agricultural sector (Haberl et al., 2007). This is also reflected by the huge area that is occupied by agriculture; almost 40% of the world's terrestrial land is agricultural land (FAOSTAT, 2015). Following the definition used by FAO and OECD, this includes arable land (28%), permanent crops (3.1%) as well as permanent meadows and pastures (68.4%) (FAO, 2013, Table 4). *Pastures* as the most widespread form of agricultural land are of particular importance, especially in drylands where climatic conditions such as scarce and highly variable precipitation make crop farming difficult. Accordingly, pastoralism often represents the only income source for people in these regions and poverty alleviation as well as

the maintenance of resilient pastures are important societal challenges. *Arable land*, i.e., the second most widespread form, represents the major natural resource for humans' agricultural activity; namely almost 50% of total human appropriation of net primary production comes from cropping (Haberl et al., 2007). Arable farming is of particular importance in Europe representing the most widespread form of agricultural land use (Stoate et al., 2002). It serves as important food and income source and traditionally served as valuable habitat for a unique flora and fauna (e.g., farmland birds (Benton et al., 2003) or vascular plants adapted to arable habitat (Storkey et al., 2012)). However, intensification of arable farming in the second half of the 20th century led to alarming negative environmental impacts such as biodiversity loss, increased greenhouse gas emission, soil erosion or water pollution (e.g., Robinson and Sutherland, 2002; Benton et al., 2003; Krebs et al., 1999; Burney et al., 2010; Vitousek et al., 1997). Therefore, the main challenge of arable farming in Europe is to identify synergistic options that harmonize the supply of agricultural products with nature conservation.

One response to these multiple challenges is the introduction of *policy options* aimed at steering land use activities towards the societal goals. However, it is difficult to empirically foresee unintended consequences of the policy options prior to their deployment in agricultural systems. Negative side effects such as land use conflicts or adverse environmental impacts like the degradation of natural resources or the loss of ecosystem services may result. As far as the two agricultural contexts (i.e., arable farming in Europe and pastoralism in drylands) are concerned, recent examples illustrate this problem. In southern Ethiopia, for instance, supporting pastoralists in maintaining their livestock in periods of drought through respective subventions led to a critically increased grazing pressure after drought and subsequently to negative effects on the pasture state (Homann et al., 2008). Another widespread type of political interventions are instruments that act through market mechanisms by steering land use activities by influencing the demand or cost side. Here, the risk of high public costs of errors exists as a side effect. This was reported for the "NaWaRo bonus" (renewable raw material bonus) in earlier versions of the German Renewable Energies Act (EEG) (cf. Britz and Delzeit, 2013) that led to an enormous expansion of bioenergy production and an intensification of land use conflicts with food production. Therefore, it is important to evaluate policy options in agricultural systems prior to their implementation with the aim to identify options for enhancing their effectiveness and mitigating side effects.

A second response to the challenge of advancing sustainable land management are *communication strategies* that enable to bridge the gap between science and society. This is highly desirable because human consumption behavior strongly influences natural ecosystems (Butchart et al., 2010) and expert knowledge of stakeholders is valuable in environmental decision-making (Reed, 2008). Moreover, this is increasingly relevant given the tendency that the state loses its influence on societal development, while the behavior of the civil society becomes more important (participation instead of command and control). Therefore, the complex feedbacks

between drivers (e.g., consumption behavior and policy options), pressure (e.g., induced land use change) and its social and environmental impacts need to be communicated to stakeholders and the wider public. However, this is a non-trivial task and innovative communication tools need to be developed and tested.

The two response fields "novel policy options" and "communication strategies" are elaborated in more detail in the following two sections.

1.1.1 *Response field "Novel policy options in agricultural systems"*

Science-based analyses of policy options in agricultural systems can help to understand their consequences prior to their implementation and to identify determinants for both enhancing their effectiveness and avoiding negative side effects such as cost explosion or environmental degradation. Therefore, one crucial factor to be considered when analyzing policy options is the individual land user because his/her decisions, e.g., on crop choice or the regime of utilizing specific resources such as supplementary fodder, determine substantially the effect that political interventions have. In other words, the farmers' decisions determine the resulting land use patterns (Valbuena et al., 2008) and with that the fulfillment of the intended societal goals, the subsequent environmental impacts and the overall performance of related policy options.

Two case studies for novel policy options are (i) promoting perennial woody crops in European agricultural landscapes for a sustainable bioeconomy and (ii) governmental supplementary feeding programs to cope with climate risks in pastoral systems in drylands. In both cases, the mentioned policy options intend to promote novel agricultural management strategies that are considered as answers to multiple challenges. They need to be evaluated to enhance their effectiveness and avoid unintended negative side effects. The following paragraphs will characterize these two fields of policy intervention and outline their relevance, the associated risks and specific research questions.

(i) An innovative strand of perennial woody crops are short rotation coppices (SRCs). SRCs consist of fast-growing trees which are grown as perennial crops on arable land (Figure 1.1a). Their investigation is relevant because SRCs are seen as a synergistic option to meet the increasing wood demand (Mantau et al., 2010; Kaltschmitt, 2011; Bentsen and Felby, 2012) and to fulfill multiple bioeconomic purposes: they serve as material source and as feedstock for heat and electricity generation. At the same time, SRCs are thought to increase biodiversity (Holland et al., 2015; Sage et al., 2006; Rowe et al., 2011) and positively affect soil and water quality (Makeschin, 1994; Schmidt-Walter and Lamersdorf, 2012). Because of all these expected advantages, SRCs are politically fostered by the provision of investment subsidies and by counting SRCs as ecological focus areas to receive payments under the reformed Common Agricultural Policy of the European Union. Despite a steadily growing wood demand (Cocchi et al., 2011), the expected environmental

(a) SRC plantation in Germany

(b) Livestock in Namibia

Figure 1.1: Examples for the two agricultural contexts investigated in this thesis. Source: (a) "Weide in einer Kurzumtriebsplantage" by Paul Schulze, Humboldt University of Berlin, licensed under Creative-Commons (CC-BY 4.0): http://creativecommons.org/licenses/by/4.0/deed.en, (b) Birgit Müller - Helmholtz Centre for Environmental Research - UFZ.

advantages and the political promotion, SRC area is with 30.000 ha still marginal in Europe (Mantau et al., 2010). Various reasons for the slow uptake of SRC cultivation are being discussed in the literature such as high initial investment costs (Styles et al., 2008) and uncertain returns (Finger, 2016). Still, the relative importance of different barriers that hamper SRC expansion is not fully understood so far. In addition, besides the positive impacts also negative environmental impacts of SRCs, such as a reduced groundwater recharge due to lower percolation of willow and poplar species, are being reported (Dimitriou et al., 2011) but also not yet fully understood. While benefits of SRCs are conceptually mainly addressed at the regional scale (e.g., Manning et al., 2015), their environmental impacts are typically assessed at the plot/field scale (e.g., Milner et al., 2015). However, an expansion of SRCs alters land use mosaics with the risk to cause land use conflicts and impacts on biodiversity and ecosystem services at the regional scale as well. Therefore, approaches to identify and investigate determinants of SRC expansion and to examine regional-scale environmental and social impacts are needed in order to assess the appropriateness of SRCs as way to advance a sustainable bioeconomy.

(ii) The second part of this thesis deals with governmental supplementary feeding programs to cope with climate risks in pastoral systems in drylands (Figure 1.1b). Pastoralists face income risks caused by the highly variable precipitation and the reported increasing frequency of droughts both resulting in shortage of fodder, a necessarily reduced livestock and finally income loss (Sissoko et al., 2011). Therefore, management strategies and policy options are needed to alleviate poverty and secure pastoralists' livelihoods while sustaining the ecological integrity of the rangeland. One prominent policy option to cope with this challenge is subsidized supplementary feeding in times of natural fodder shortage. In many pastoral regions in drylands, for instance in North Africa and West Asia, this is implemented as a govern-

mental risk-coping strategy (Hazell, 2000, p. 93) or as part of development projects (cf. the Project of Pastoral Development and Livestock in the Oriental PDPEO in Morocco, Mahdi (2007)). This management practice, however, is also strongly debated because enabling the maintenance of high livestock numbers during droughts may lead to an increased grazing pressure and an accompanied higher risk of rangeland degradation. Thereby, the design of the supplementation strategy (e.g., timing of supplementation) might mitigate such negative side effects. Systematic assessments of chances and risks of alternative supplementation strategies in the form of governmental subsidies are missing so far. In addition, subsidy programs are accompanied by high costs for the society and their efficiency is often questionable. Therefore, studies on the appropriateness of such programs are urgently needed to ensure cost-efficiency and to avoid unintended side effects.

In both cases, policy options that promote novel agricultural management strategies emerged as answer to multiple societal challenges. These need to be evaluated with regard to both their effectiveness and their social and environmental impacts. Moreover, a worldwide coverage with case studies assessing the appropriateness of these policy options is not feasible. Therefore, ways to assess the transferability of results between regions are desirable (Meyer et al., 2015). This is especially relevant for policy impact analysis as effects of novel policy options may depend on the regional context and, thus, may differ between regions. For example, Huber et al. (2013) promote regional-specific policy instruments, which exploit the potential of regions by taking their specific characteristics into account.

1.1.2 *Response field "Communication strategies"*

Besides agricultural land use decisions, consumption decisions are a crucial driver of land use change. Human consumption puts enormous pressure on natural ecosystems (Butchart et al., 2010). Therefore, adaptation of consumption behaviors is seen as crucial determinant for a sustainable development of the global human-environment system (WBGU, 2011; Raskin et al., 2002; Leiserowitz et al., 2006). For example, shifting diets is seen as one approach to advance sustainable land management (Foley et al., 2011). This is, however, a challenging task because human behavior strongly depends on the peoples' state of knowledge. Therefore, increasing public awareness of the link of consumption decisions and environmental problems may help to encourage environmental-friendly behavior. A further widely accepted approach to enhance sustainable land management is the integration of stakeholders via participatory methods (Rounsevell et al., 2012; Voinov and Bousquet, 2010). Stakeholder participation can enhance the quality of environmental decisions by incorporating comprehensive and valuable expert knowledge (Reed, 2008).

In order to raise public awareness and integrate stakeholders, it is necessary to communicate the complexity of sustainable land management beyond the scientific community. This is a non-trivial task that requires innovative communication strat-

egies. One promising approach that is gaining more and more attention are educational games (Barreteau et al., 2007). However, the development and evaluation of such innovative tools is challenging and benefits from the knowledge of interdisciplinary teams of social and natural scientists.

1.2 RESEARCH OBJECTIVES OF THIS THESIS

The overarching research objectives of this thesis are:

i. Evaluation of (existing and novel) policy options in agricultural systems intentionally designed to cope with a variety of societal challenges in terms of effectiveness and side effects; identification of options to mitigate unintended side effects and steer towards more sustainability.

ii. Design and evaluation of communication strategies, particularly games, for environmental education and stakeholder integration.

Within the first objective (i.), we aim at the evaluation of policy options promoting SRCs in order to contribute to a sustainable bioeconomy as a first case study (Figure 1.2). Here, we characterize determinants of SRC expansion and assess regional-scale impacts of SRCs on biodiversity and multiple ecosystem services, the analyses of which are lacking so far. As a second case study, we aim at the evaluation of governmental supplementary feeding programs to cope with climate risks in pastoral systems in drylands (Figure 1.2). Here, we assess potential benefits and threats of conventional and novel strategies of supplementary feeding in the form of government subsidies.

We approach these research objectives by the means of dynamic social-ecological simulation models (Figure 1.2) as they enable to depict causal relationships between policies, land use change and environmental and social impacts at different temporal and spatial scales and to assess the dependence of model outcomes on the regional context. The methodological background and challenges will be presented in the following section.

1.3 METHODOLOGICAL BACKGROUND

1.3.1 *Land use modeling*

Land use models are used to study the dynamics of land use and land cover change (LUCC) and how it is influenced by policies and management strategies (Agarwal et al., 2002). Land cover refers to the surface of the earth, while land use depicts the purpose for which human use this land cover (cf. Lambin et al., 2000). For example, forests represent a land cover that can be used for recreation, timber production,

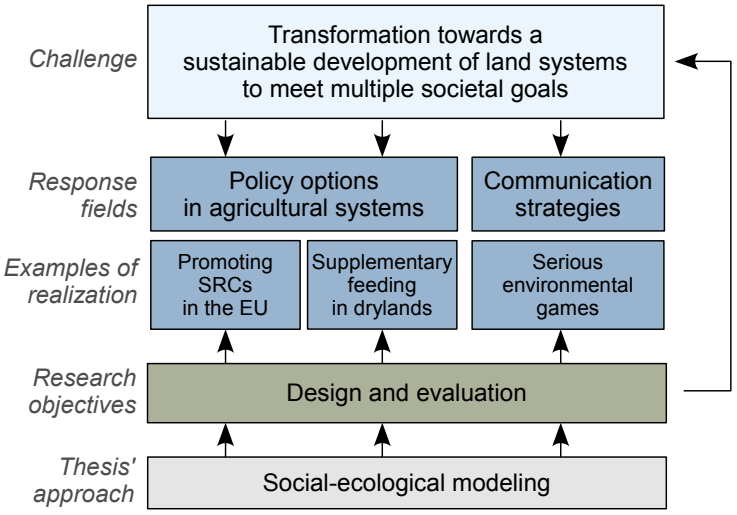

Figure 1.2: Schematic overview of the aim, the focus and the approach of this thesis.

carbon sequestration or the maintenance of biodiversity (Lambin et al., 2000). Another land cover is grass which can be found in different land uses such as pastures or urban parks (Fisher et al., 2005).

Land use models can be differentiated with respect to the two dimensions *model type* and *unit of representation*. First, often two *model types* are distinguished: empirical/statistical models and process-based models (cf. Turner et al., 2007; Veldkamp and Lambin, 2001; Agarwal et al., 2002). Statistical approaches give insights into historical land use and land cover changes by using "multivariate regression techniques to relate land use change to spatial characteristics and other drivers" (Heistermann et al., 2006, p. 144). Statistical approaches provide limited use for assessing future scenarios of LUCC. For this purpose, process-based models are valuable because they depict processes and interactions between different components of the system and enable explorations of responses to changing environmental or socio-economic conditions (Lambin et al., 2000).

Second, land use models can be further differentiated by the *unit of representation*. They can either (1) describe the human-environment interactions as a whole system (e.g., IMAGE[1], CLUE[2]) or be designed (2) "at the scale of agents that represent individual units of decision-making" (Turner et al., 2007, p. 20668). The first type, i.e., the system-based modeling approach, is characterized by transition rules that are equally applied over the whole landscape. These can, for example, be empirically derived probability functions based on pixel characteristics combined with dynamic decision rules such as reduced transition rates of certain land uses (e.g., Verburg et al., 2002). In contrast, the second type, i.e., modeling approaches referring to

1 themasites.pbl.nl/models/image/index.php/Welcome_to_IMAGE_3.0_Documentation
2 ivm.vu.nl/en/organisation/departments/spatial-analysis-decision-support/CLUE

the individual scale, links pixels to people and aims at representing land use as a result of human decision-making in the considered region. Here, especially agent-based models which depict the decision-making of multiple individual land users interacting with each other and the environment have been increasingly applied in land use science (Groeneveld et al., under review). Agent-based models are seen as strong tools to study LUCC because they can incorporate aspects such as adaptation or learning (Parker et al., 2003; Matthews et al., 2007; Rounsevell et al., 2014).

In particular, process-based models at the individual scale enable the assessment of policy options in the form of virtual laboratories (Dibble, 2006; Baumgärtner et al., 2008; Schlüter et al., 2012; Heppenstall et al., 2012; Seppelt et al., 2013). Agricultural policy options can be tested in a safe virtual environment without direct consequences in real landscapes (Berger, 2001; Happe et al., 2006). Thereby, the depiction of the interplay between social and ecological systems enables the evaluation of policy options from different perspectives and with regard to different intended societal goals (e.g., poverty alleviation, climate mitigation). Going beyond the sole evaluation of existing policy options, these models then also enable to vary specific settings of policy options (such as temporal regimes of utilizing subsidized supplementary fodder) and therewith can help in designing novel policy options. However, this policy analysis requires operationalizing the effect of policy options on land use decisions and subsequently their effects. Therefore, multiple determinants as well as the direct consequences of land use decisions on land use patterns, economic markets or environmental conditions of the land need to be appropriately depicted in the model.

Furthermore, land use modeling facilitates to address the research need stated in Section 1.1.1: the need to analyze the transferability of policy impacts between regions (e.g., Huber et al., 2013; Fritsch and Stephan, 2005; Kleijn and Baldi, 2005; Wretenberg et al., 2010). First, human responses to policy options and available land management options depend on the regional context (Rounsevell et al., 2012). Second, land use impacts such as effects on biodiversity or ecosystem services differ between regions also (e.g., Reidsma et al., 2006). However, a worldwide coverage with case studies evaluating policy options is not feasible which is why ways to assess the transferability of results between regions are desirable (Meyer et al., 2015). One approach is to empirically identify "generic, archetypical patterns of land use transitions" (Rounsevell et al., 2012, p. 7). Ellis and Ramankutty (2008), for example, propose a classification of anthropogenic biomes based on empirical analyses of data on land cover, irrigation and population. This concept has been further developed by incorporating additional factors such as livestock density or market accessibility (Letourneau et al., 2012; van Asselen and Verburg, 2012). Recently, Vaclavik et al. (2013) advanced this approach by performing a data-driven identification and mapping (instead of being based on predefined assumptions) of land system archetypes which are characterized by the same combinations of land use intensity, environmental conditions and socio-economic factors. This heavily data-dependent approach enables to detect general drivers and impacts of land use

change and provides "means to target regionalized strategies to cope with global change" (Vaclavik et al., 2013, p. 1637). However, impact assessments of specific policy options in agricultural systems need to depict feedbacks between the local scale including land use decisions and regional-scale impacts (Verburg, 2006). This requirement can be addressed by an alternative approach of transferability analyses: process-based models in combination with stylized landscapes. Stylized landscapes are not real geographic landscapes, but depict the key ecological or landscape characteristics of a region. Stylized landscapes enable to derive a general understanding that is valid for more than one specific region (Dibble, 2006). In a spatially explicit setting this especially requires the generation of underlying maps of factors that influence land use decisions for example via spatially heterogeneous yields, costs or environmental conditions. This enables to test the relevance of explicit spatial configuration by quantifying the in model predictions due to variation in spatial structure (termed spatial uncertainty analysis by Jager et al. (2005)). Moreover, regional spatially aggregated characteristics (e.g., recovery rate of the vegetation or the spatial correlation of natural characteristics) can be easily varied in stylized landscapes in the form of scenarios to represent different region types. Here, it is a challenge to ensure the appropriateness of stylized landscapes with regard to their ability to depict real landscapes.

Overall, if these challenges are met, social-ecological process-based stylized models at the individual scale represent a promising tool to assess policy options with regard to their appropriateness in tackling the multiple societal challenges that led to their emergence in the first place.

1.3.2 *Tools for environmental education*

In Section 1.1, the importance of effective tools for environmental education and communication was outlined. Numerous transdisciplinary approaches beyond formal research publications exist that can help to bridge the gap between science, stakeholders and the interested public. Examples include atlases (Settele et al., 2008, 2010; Rasmont et al., 2015), decision support tools (McCown, 2002; Frank et al., 2002; Matthies et al., 2007; Mewes et al., 2015; Ulbrich et al., 2008), rules of thumb (Frank and Wissel, 1998; Etienne and Heesterbeek, 2001; Frank, 2004) or videos and flyers (such as provided by the research project Sustainable Land Management[3]). Serious games resemble an innovative approach, which gains more and more attention (Michael and Chen, 2005; Barreteau et al., 2007). Serious games are games that are not used exclusively for entertainment, but primarily aim at conveying information and education. Examples for serious games in the environmental

3 nachhaltiges-landmanagement.de/en/home/

field include board games such as KEEP COOL (Eisenack, 2012) and NomadSed[4] or computer games such as ECOPOLICY[5].

While these examples demonstrate that many promising tools and, particularly, games exist, an online game demonstrating the impact of policy instruments on sustainable land management is missing so far. Moreover, a consistent validation of experimental learning methods is also often lacking (Gosen and Washbush, 2004).

1.4 CHAPTER OVERVIEW

In Section 1.1, the potentials and challenges of the evaluation and design of appropriate policy options in agricultural systems and of communication strategies for advancing sustainable land management were outlined. Subsequently, the overarching and specific research objectives of this thesis were derived in Section 1.2. Finally, the methodological background and challenges of the approach taken in this thesis to achieve the research objectives were presented in Section 1.3.

In this thesis, we develop and evaluate dynamic process-based models at the individual scale to study politically fostered land use changes and their consequences in the context of two exemplary agricultural systems. This is done in order to evaluate the effectiveness and side effects of policy options that were intentionally designed to cope with multiple societal challenges, but may cause unintended social or environmental risks that should be mitigated. These two case studies are the political promotion of short rotation coppices (SRCs) in European agricultural landscapes seen as contribution to a sustainable bioeconomy (Part I) and governmental supplementary feeding programs to cope with climate risks in pastoral systems in drylands (Part II). These two studies on the use of process-based and agent-based land use models for analyzing policy options are complemented by the development of a serious online game on sustainable land management in general to provide a communication tool for environmental education and stakeholder integration (Part III). In the following paragraphs, the three single parts and the chapters they comprise are presented in more detail.

In Part I, which comprises Chapter 2 and 3, we study the policy option of promoting SRCs as an option to sustainably meet the growing wood demand.

Chapter 2: In this chapter, we develop a spatially explicit agent-based model to study SRC expansion as a special form of regional land use change that is driven by decisions of individual land users responding to politically fostered economic incentives. The aim is to achieve a comprehensive mechanistic understanding of the determinants of SRC expansion and the relative importance of both landscape-structural context and economic settings. Because of this generic focus, the modeling work is based on virtual stylized landscapes. Therefore, we operationalize policy options that promote an SRC expansion and their impact with regard to the

4 info.nomadsed-spiel.de/index.php/de

5 frederic-vester.de/deu/ecopolicy

steering of profit-maximizing farmers, which have to choose between conventional annual crops, SRCs and abstaining from agriculture. Furthermore, we develop a landscape generator for the underlying maps of factors that influence these decisions. Subsequently, we assess resulting land use patterns in terms of SRC coverage and distribution. We characterize the relative importance of economic and environmental as well as general and location-dependent determinants of SRC cultivation decisions. Finally, we develop and apply different approaches of transferability analyses and test the robustness of the derived results within region types differing in the spatial explicit configuration as well as between region types by working with stylized landscapes.

Chapter 3: In this chapter, we apply the agent-based model to a specific case study - the Mulde watershed in Central Germany. Subsequently, we quantify the regional-scale impacts of SRCs on multiple ecosystem services and biodiversity. Therefore, we model cultivation decisions of profit-maximizing farmers under different economic scenarios based on the spatially explicit agent-based model presented in Chapter 2. In addition, we assess two policy scenarios in which SRCs are cultivated to fulfill the requirements of the Common Agricultural Policy of the European Union. For all scenarios, we model ESS bundles for the modified landscape configuration. That is, at this regional scale, we evaluate the impact of SRC expansion on crop yields, carbon storage, nutrient and sediment retention, as well as biodiversity by using environmental and ESS assessment models.

In Part II of this thesis, which comprises Chapter 4, we investigate governmental supplementary feeding programs to cope with climate risks in pastoral systems in drylands.

Chapter 4: In this chapter, we develop a process-based ecological-economic rangeland model, which accounts for the feedback between the stocking decisions of a single pastoralist depending on subsidized supplementary fodder and the vegetation dynamics of the pasture and its long-term consequences. We assess the potential benefits and threats of conventional and hypothetical strategies of supplementary feeding in the form of governmental subsidies. Therefore, we investigate the cost-efficiency performance of governmental supplementary feeding programs in achieving poverty alleviation and the maintenance of resilient pasture. Finally, we perform a further approach of transferability analysis and test the robustness of results between regions differing in the ecological characteristics of the rangeland utilization system.

In the last part (Part III), which comprises Chapter 5, we develop a specific communication tool for environmental education and stakeholder integration.

Chapter 5: In this chapter, we develop and test the model-based serious online game LandYOUs on sustainable land management. LandYOUs lets the player step into the role of a politician governing a virtual country by the means of different policies. By

these partolicies, the player determines the land use and subsequently a set of interdependent indicators such as human well-being, environmental quality and financial resources. The model underlying LandYOUs is implemented as time-discrete system dynamics model, which is complemented by a spatially explicit landscape. This game design allows visualization of spatially explicit land use changes and the incorporation of complex system dynamics and is, thus, particularly suitable in the field of land use management. In addition, we perform a survey-based evaluation of LandYOUs to gain insights into the appropriateness of online games. The development, test and improvements of LandYOUs benefit from integrating knowledge of an interdisciplinary research team of land use modelers, economists, graphic designer, software engineers and environmental didacts.

The last part (Part IV), which comprises Chapter 6, completes this thesis.

Chapter 6: Subsequent to the presentation of the three single parts, Chapter 6 summarizes the main results, discusses strengths and limitations of the applied methods and gives an outlook on future studies.

Part I

PROMOTING SHORT ROTATION COPPICES IN THE EU

2

THE EXPANSION OF SHORT ROTATION COPPICES: CHARACTERIZATION OF DETERMINANTS WITH AN AGENT-BASED LAND USE MODEL

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2.1 ABSTRACT

Wood is a limited resource which is exposed to a continuously growing global demand not least because of a politically fostered bioenergy use. One approach to master the challenge to sustainably meet this increasing wood demand are short rotation coppices (SRCs). However, the cultivation of SRCs is only gradually evolving and it is not fully understood which determinants hamper their expansion.

This study provides a theoretical understanding of the economic and environmental determinants of an SRC expansion. This assessment requires the incorporation of farmers' decision-making based on an explicit investment appraisal. Therefore, we use an agent-based model to depict the decision-making of profit-maximizing farmers facing the choice between SRCs, conventional annual agricultural activity and abstaining from cultivation (fallow land). The land use decisions are influenced by general economic determinants, such as market prices for wood, and by site-dependent determinants, such as the soil quality. We found that the willingness to pay for SRC products most strongly influences the coverage of SRCs in the landscape. The site-dependent soil quality also heavily influences the SRC cultivation decision: SRCs will in most cases be established on sites with low productivity. In contrast to the impact of the soil quality, our model results indicate that the impact of the distance to processing plants on farmers' decisions strongly depends on general economic determinants and the given spatial structure of the underlying natural landscape. Analyzing the relative importance of different determinants of an SRC expansion, this study gives insights on the approach of using SRCs to sustainably meet the growing wood demand. Moreover, these insights are taken as a starting point for the design of effective government interventions to promote SRCs.

2.2 INTRODUCTION

Wood is a limited bio-based resource that serves as a source for material, power and heat. The global wood demand is increasing due to economic growth and demographic change (FAO, 2014). Lamers et al. (2012) depicted a more than ten-fold increase in EU demand for wood pellets and an exponential increase in global trade of wood pellets from 0.5 Mt to 6.6 Mt between 2000 and 2010. This increase is expected to be further pushed by the growing relevance of the bioeconomy, i.e., the enclosure of all economic sectors that develop, produce or use bio-based renewable resources. At the UN Conference on Sustainable Development 2012 in Rio de Janeiro, the international community committed to implement the "Green Economy" as an important tool of sustainable development (UN, 2012). At the European level, the European Commission has presented a bioeconomy strategy in 2012 that aims at a low-carbon and resource-efficient economy (European Commission, 2012). The Netherlands, Denmark, Sweden, Finland, Germany, Canada and the United States have presented national bioeconomy strategies, and other countries are expected to

follow (BMEL, 2014). The associated stronger role of bio-based resources including innovative wood uses may even further increase the wood demand in the future.

As a consequence, the challenge is to meet the increasing wood demand without negative environmental effects. Woodland and natural forests provide multiple regulating ecosystem services such as carbon storage or purification of water and air. Furthermore, forests are a habitat for about 80% of world's terrestrial biodiversity (IUCN, 2012). They are cleared at the rapid rate of about 13 million hectares per year leading to severe negative environmental impacts. For example, in 2010, 11% of all anthropogenic greenhouse gas emissions originated from the sector of forestry and other land uses (IPCC, 2014). Therefore, a variety of policy instruments aiming at protecting forests and avoiding such negative impacts are implemented worldwide (e.g., German Federal Forest Act, Código florestal in Brazil, or REDD+). These policies set limits to the amount of wood that can be sourced from forests.

An alternative approach to meet the increasing wood demand are short rotation coppices (SRCs). SRCs consist of fast-growing trees, in the EU mostly poplar and willow species, which are grown as perennial energy crops on agricultural land (Njakou Djomo et al., 2015). SRC plantations are harvested every few years and afterwards stump sprouting takes place. After several of these rotations, the land is recultivated. SRCs may fulfill multiple bioeconomic purposes: they serve as source of material, heat and power. At the same time, several environmental advantages over conventional agriculture are being discussed (for overviews of environmental impacts of SRCs see BfN (2012), Thrän et al. (2011) or Weih and Dimitriou (2012)). For example, SRCs are expected to have a positive effect on biodiversity (Sage et al., 2006; Rowe et al., 2011; Holland et al., 2015) as well as on soil and water quality (Makeschin, 1994; Schmidt-Walter and Lamersdorf, 2012). Nonetheless, environmental benefits of SRCs are strongly dependent on site- and plantation-specific characteristics (e.g., tree species, cultivation design). Negative impacts, for example on the water balance, can also occur (e.g., Dauber et al., 2010; Thrän et al., 2011; Strohm et al., 2012). Still, positive impacts predominate and SRC expansion is seen as promising approach to sustainably meet the growing wood demand.

However, the expansion of SRCs is proceeding slowly. For example, for Germany and the year 2013, Drossart and Mühlenhoff (2013) reported an area of approximately 6500 ha SRCs which only represents 0.03% of the total agricultural land (FAOSTAT, 2015). For the UK and the year 2014, the Department for Environment and Food and Agriculture reported an area 2849 ha (DEFRA, 2015) or 0.02% of total agricultural land (FAOSTAT, 2015). Finally, for Sweden and the year 2011, Dimitriou et al. (2011) reported an area of 14000 ha willow SRC cultivations or 0.5% of total agricultural land. Past studies have predicted strong increases in SRC for several European countries. For example, in the 1990s, stakeholders predicted that the SRC area in Sweden would increase to several hundreds of thousands of hectares (Helby et al., 2004). Almost two decades later, the European Environment Agency in 2006 still stated that SRCs would substantially increase from 2010 onwards (EEA, 2006). Given the above stated statistics on current cultivation areas,

it becomes evident that these predictions have failed so far. At the same time, EU wood pellet demand increased by 43.5% from 2008 to 2010 (Cocchi et al., 2011).

Various reasons for the slow uptake of SRC cultivation in Europe are being discussed in the literature. Main barriers include high initial investment costs combined with uncertain returns on investment. The high uncertainty is caused by price volatility (Finger, 2016) as well as by uncertain yields and production costs (Strohm et al., 2012). In such a situation, it is a good strategy to postpone investment in order to wait for the occurrence of learning curve effects (Musshoff, 2012; de Wit et al., 2013). In addition, capital (especially land) is bound for a long time, leading to inflexibility to react to changing market developments (Strohm et al., 2012; Schweier and Becker, 2013). Still, the relative importance of different determinants that hamper SRC expansion in the EU is not fully understood.

Empirical analyses of spatial distributions of SRCs are one approach to identify such determinants. For example, Mola-Yudego and Gonzalez-Olabarria (2010) use a geostatistical method to depict determinants of SRC establishment in Sweden. However, low SRC establishment leads to low data availability on commercial plantations and therefore only a few studies exist, which focus on specific regions. We believe that this issue can be tackled by considering SRC expansion as a result of land use decisions and by analyzing the decision-making within a modeling framework. Agricultural decisions, like the cultivation of SRCs, are mostly driven by expected profits and so expected revenues and costs. These can depend on both site conditions (e.g., soil quality) and factors that are not site-specific (e.g., market conditions). For our analysis, we will refer to them as site-dependent determinants and general economic determinants. Soil quality and transportation costs to the next woody biomass processing plant are important site-dependent determinants for the economic feasibility of SRCs (cf. Faasch and Patenaude (2012) and Dunnett et al. (2008) respectively). Wood demand, prices for agricultural products and cost patterns are important general economic determinants. At the time being, the interplay of individual land use decisions with general economic and site-dependent determinants has not been analyzed. This may be owed to the complexity of the underlying decision mechanisms which evolves from the need to compare crops with harvest cycles of different lengths.

This study investigates how the above mentioned economic and environmental determinants affect SRC expansion in terms of the increase in land cover and spatial distribution of plantations. Therefore, we focus on the European context and analyze the relative importance of site-dependent determinants and general economic determinants. More specifically, we investigate the two site-dependent determinants “soil quality” and “distance to woody biomass processing plants” as well as seven general economic determinants such as “willingness to pay for agricultural products” or “investment expenditures”. In addition, we test the transferability of model results between regions by analyzing to what extent these findings depend on the spatial structure of the underlying natural landscape. Therefore, we assess the relevance of the explicit spatial configuration and of aggregated spatial charac-

teristics of the underlying landscape. For this purpose, we develop a spatially explicit agent-based model (ABM) to depict the decision-making of profit-maximizing farmers in a stylized landscape indirectly interacting via a market mechanism. This approach enables us to simulate and analyze land use decisions under different economic framework conditions and in differently structured stylized landscapes. This leads to an improved general system understanding as opposed to a specific case study. We take these insights as a starting point to discuss the design of effective government interventions to promote SRCs. Finally, we conclude by reflecting on the potential of the applied modeling approach.

2.3 MATERIAL AND METHODS

In the following, we present the model INCLUDE (INdividual Cultivators' Land Use DEcisions). It is based on an agent-based model (ABM) developed by Weise (2014): a stylized model of rational land use decisions that comprises markets and policy instruments to assess land use effects of promoting bioenergy. We expand this model to enable the incorporation of spatial heterogeneity and of an explicit investment appraisal to include crops with harvest cycles of different lengths.

2.3.1 *General conception*

The model INCLUDE considers regional land use change as result of individual land use decisions. The landscape is described as regular grid of cells. In each cell, there is one agent (i.e., farmer) who decides on the crop to be cultivated in the next time step. The agents are assumed to be rational profit maximizers with full knowledge over revenue and costs of all possible land use options. We believe that profit maximization is an appropriate assumption for decisions in the European industrial agricultural sector.

In the model, agricultural markets are assumed to be endogenous and to mediate interactions among agents. Therefore, equilibrium market prices for both SRC products and products based on annual crops are described in the model by the ratio of exogenously given demands and the endogenously resulting supply that is determined by the agents' cultivation decisions. This price formation is in line with standard economic theory (e.g., equilibrium concept; cf. Mankiw and Taylor (2006) or Engelkamp and Sell (2007)) and incorporates the critical market feedback of supply decisions that result in prices which influence again supply decisions (as also used by Lawler et al. (2014)). In the result of the individual decisions of all agents and the interactions mediated by the market mechanism, land use patterns emerge and evolve over time. These patterns are evaluated afterwards.

Incorporating SRCs as an agricultural option comes along with several challenges. As stated above, several determinants influence the SRC cultivation decision by determining revenue and costs incorporated in the profit calculation. We assume that

the agents' land use decisions are influenced by site-dependent (i.e., different between cells) and general economic determinants (i.e., same for all cells). All determinants investigated in this study are shown in Table 2.1.

Table 2.1: Determinants of land use decisions in the model.

	Determinants	**General**	**Site-dependent**
Economic	Aggregated willingness to pay for SRC products	×	
	Aggregated willingness to pay for annual crops	×	
	Investment expenditures	×	
	Discount rate	×	
	Recovery costs	×	
	Harvest costs	×	
	Transport price	×	
	Distance to processing plant		×
Environmental	Soil quality value in cell		×

To address the site-dependent determinants, we need to incorporate spatial heterogeneity. Moreover, as we aim to gain general understanding of SRC expansion, rather than exploring a specific region, we decided to investigate stylized landscapes. The underlying landscape is generated using a randomization algorithm which allows generating a variety of landscapes that coincide in certain aggregated spatial characteristics but differ in their explicit spatial configuration. This enables to test the transferability of results between landscape types. Each generated landscape consists of a grid of cells with both specific soil qualities and locations of woody biomass processing plants (see Figure 2.1). These site-dependent determinants together with the general economic determinants influence the agents' land use decisions and hence the emerging land use pattern (Figure 2.1). The approach of combining the ABM and a landscape generator enables us to systematically investigate the relative importance of the general economic and site-dependent determinants for the SRC cultivation decisions.

In addition to the spatial heterogeneity, the perennial character of SRCs requires the incorporation of an explicit investment appraisal. INCLUDE runs on an annual temporal scale as annual crops are also included. To enable the comparison between land use options with different lengths of harvest cycles, the equivalent annual annuity approach from investment theory was chosen (e.g., Brigham and Houston, 2006). This approach calculates a constant annuity from an uneven cash flow for several periods. In a first step, the net present value for the investment is calculated by discounting the annual profits. In a second step, this net present value is

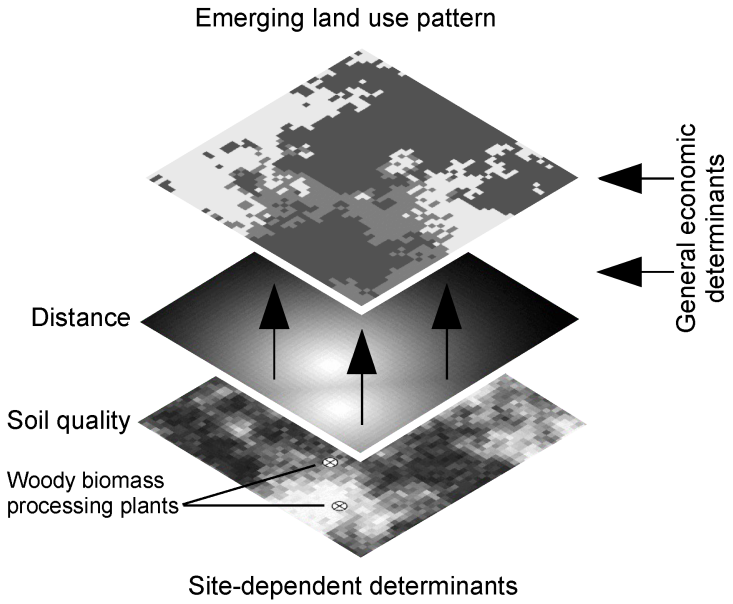

Figure 2.1: Interplay of site-dependent and general economic determinants in the course of the SRC expansion.

multiplied by the annuity factor to receive a constant value per year, the equivalent annual annuity. Discount rates are seen as subjective discount rates which can vary depending on personal risk aversion (Barberis and Thaler, 2003). Therefore, different levels of risk perception can be analyzed with the model. This approach is appropriate as it is often recommended to farmers interested in SRC practice (for example Schweinle and Franke (2010) or the profitability calculator provided by the AGROWOOD research project (AGROWOOD, 2015)) and has been used in several studies on the financial analysis of SRC (Kasmioui and Ceulemans, 2012).

2.3.2 *Initialization of landscape*

At the beginning of each simulation, the underlying landscape is randomly generated: (1) soil qualities are assigned to cells and (2) woody biomass processing plants are spatially allocated within the landscape.

(1) The distribution of soil quality for the ABM was generated using a randomization algorithm that returns uniformly distributed, spatially correlated numbers with fixed arithmetic mean and a certain spatial correlation. For this purpose, the method of Cholesky decomposition, which considers the covariances among all cells, was used (see Appendix A in Thober et al. (2014) for details). This enables the generation of landscapes with different aggregated spatial characteristics of soil quality distribution, i.e., mean and spatial correlation (see Figure 2.2).

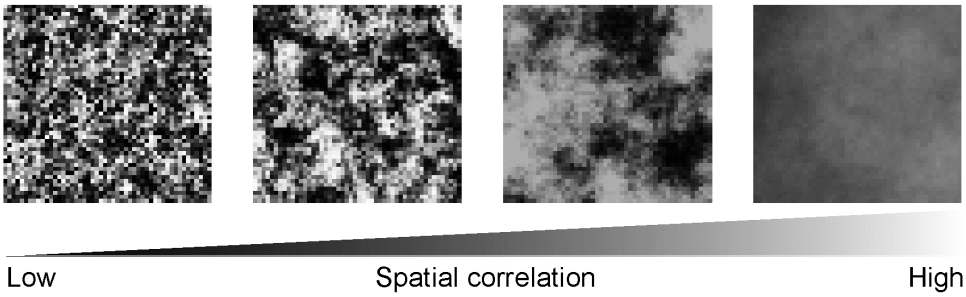

Figure 2.2: Examples of generated landscapes with increasing spatial correlation from left to right.

(2) A fixed number of woody biomass processing plants are randomly placed within the landscape. At this, the number of processing plants can be adapted to represent regions with different areal densities (see Appendix A for standard parameter values).

2.3.3 *Model processes*

At the beginning of each decision step, the current market prices $p_j(t)$ in year t for the different products j, i.e., annual crops (ANN) and $SRCs$, are calculated based on the regional supplies $H_j(t)$ and the following pricing rule:

$$p_j(t) = \frac{D_j}{H_j(t)} \text{ with } H_j(t) = \sum_{i=1}^{n} h_j^i(t) \tag{2.1}$$

where D_j is the aggregated willingness to pay for product $j \in \{ANN, SRC\}$, n the number of agents and $h_j^i(t)$ the harvest amount of product j in cell i given by:

$$h^i_{ANN}(t) = \begin{cases} q^i & \text{, if land use is } ANN \\ 0 & \text{, if land use is not } ANN \end{cases} \tag{2.2}$$

$$h^i_{SRC}(t) = \begin{cases} q^i \cdot 0.2 + h_{min} & \text{, if land use is } SRC \\ 0 & \text{, if land use is not } SRC \end{cases} \tag{2.3}$$

where q^i is the soil quality of the cell of agent i. As pointed out by Zhang et al. (2007), soil properties strongly impact the agricultural output. Similarly, we assume that the yield of annual crops and the soil quality are linearly correlated with both factors being normalized between 0 and 1. Thereby, we follow the concept of using soil values to classify German soils (GD NRW, 2014). The soil value is a measure for differences in net yield under proper cultivation that are solely determined by differences in soil (GD NRW, 2014). With Equation 2.2, a soil value q^i of

0.5 represents a reduction in net yield by 50% of the maximum yield (cf. Petzold et al., 2014). The yield of SRCs is also assumed to decrease on poor soils (as was found by Ali (2009)). At this, the dependence on the soil quality is less pronounced than for annual production because studies showed that biomass yield from SRCs is dependent on further factors such as age of plantation or precipitation (Ali, 2009). Nevertheless, in our model, the consideration of biophysical site conditions is restricted to the soil quality due to simplicity reasons.

The land use in the cells is determined by the agents' decisions based on profit calculation. This calculation differs between the three land use options: no cultivation (NoC), ANN and $SRCs$. If agent i abstains from cultivation, neither costs nor revenue arise and the related profit Π for agent i is therefore:

$$\Pi^i_{NoC} = 0 \tag{2.4}$$

For annual agricultural production, the following profit function applies:

$$\Pi^i_{ANN}(t) = p_{ANN}(t) \cdot h^i_{ANN} - c_{ANN} \tag{2.5}$$

where $p_{ANN}(t)$ is the current market price (calculated by the pricing rule shown in Equation 2.1), h^i_{ANN} the harvest of annual crops in the cell of agent i and c_{ANN} the production costs of annuals. For the profit calculation of the SRC option, the profit of agent i in year t, $\Pi^i_{SRC}(t)$, over the whole lifetime T of the SRC is calculated by Equation 2.6. In the first year, only costs accrue, followed by both profit and costs accruing after each rotation cycle:

$$\Pi^i_{SRC}(t) = \begin{cases} -c^i_{SRC}(t) & \text{, if } t = 0 \\ p_{SRC}(t) \cdot h^i_{SRC} - c^i_{SRC}(t) & \text{, if } t \; mod \; a = 0 \\ 0 & \text{, else} \end{cases} \tag{2.6}$$

where $p_{SRC}(t)$ is the current market price in year t for SRC products produced in one rotation cycle on optimal soil conditions calculated by the pricing rule shown in Equation 2.1, h^i_{SRC} the harvest of SRCs in the cell of agent i, $c^i_{SRC}(t)$ are all incurring costs in year t calculated by Equation 2.7 and a is the number of years after which harvest takes place, i.e., the rotation cycle.

Finally, all occurring costs are calculated by Equation 2.7. In the first year, only investment expenditures v accrue. At the end of each rotation cycle, harvest costs h as well as transport costs to the processing plant Γ^i occur. Finally, at the end of the lifetime T, in addition to harvest and transport costs, recovery costs of the land r

have to be paid. In all other years, no treatments are needed and therefore no costs have to be paid:

$$c^i_{SRC}(t) = \begin{cases} v & \text{, if } t = 0 \\ h + \Gamma^i \cdot h^i_{SRC} & \text{, if } t \; mod \; a = 0 \text{ and } t<T \\ h + \Gamma^i \cdot h^i_{SRC} + r & \text{, if } t = T \\ 0 & \text{, else} \end{cases} \tag{2.7}$$

where t is the current year, v are the investment expenditures, h the harvest costs, Γ^i the transportation costs of wood produced under optimal soil quality conditions calculated by Equation 2.8, h^i_{SRC} the actual harvest of SRCs in the cell of agent i, a the rotation cycle and r the recovery costs. The transportation costs are assumed to be linearly dependent on the distance to woody biomass processing plants:

$$\Gamma^i = \tau + \gamma \cdot d^i \tag{2.8}$$

where d^i is the distance of agent i to the processing plant, τ are fixed costs for transportation and γ the transport price per distance. We assume a homogeneous cell size f to calculate the distance d using Euclidean distance (Deza and Deza, 2013).

From the sequence of profits $\Pi^i_{SRC}(t)$, the net present value is calculated as the sum of the discounted profits:

$$N^i = \sum_{t=0}^{T} (1+s)^{-t} \cdot \Pi^i_{SRC}(t) \tag{2.9}$$

where T is the lifetime of the plantation, s the discount rate and $\Pi^i_{SRC}(t)$ the profit in year t calculated by Equation 2.6. Subsequently, the equivalent annual annuity E is calculated from the net present value N to enable the comparison of land use options with unequal lifespans:

$$E^i = \frac{1}{1-(1+s)^{-T}} \cdot N^i \tag{2.10}$$

where s is the discount rate, T the lifetime of a SRC plantation and N^i the net present value calculated by Equation 2.9.

Finally, the agent compares the equivalent annual value E^i with the possible profit from annual agricultural production $\Pi^i_{ANN}(t)$ and chooses the option with the higher profit. If both, the equivalent annual value E^i of SRC and the profit of annual agricultural production $\Pi^i_{ANN}(t)$ would yield negative incomes, the agent decides to abstain from cultivation.

All model parameters, their values and the references for parameterization can be found in the Appendix A.

2.3.4 *Evaluation criteria and simulation experiments*

In this study, we investigate how different determinants affect a possible SRC expansion after entering the market in terms of the increase in SRC coverage and their spatial distribution across the stylized landscape. We assess the relative importance of different general economic and site-dependent determinants in differently structured stylized landscapes.

For this purpose, we apply an ensemble approach and perform a spatial sensitivity analysis as follows. The underlying landscapes within an ensemble show the same aggregated spatial characteristics and only differ in their explicit spatial configuration. Accordingly, the variance in the outcomes over an ensemble indicates the sensitivity of the evaluation criteria to changes in the explicit spatial configuration and so the transferability of conclusions between landscapes. Additionally, the randomization algorithm enables us to generate ensembles with different aggregated spatial characteristics. In this study, we compare two scenarios with ensembles of different spatial correlations of soil quality (cf. Figure 2.2). Therefore, we vary the spatial correlation and hold the mean soil quality constant. As a consequence, the frequency of soil qualities also changes with the spatial correlation because of the changing spatial variability. A low spatial correlation leads to a uniform frequency distribution because soil qualities of all levels are occurring. A high spatial correlation implies a clustering of soil qualities around their mean while extreme values are not occurring.

Based on this ensemble approach, we perform a systematic model analysis in two steps, which are summarized in Table 2.2 and described in detail in the following paragraphs.

In the first step, we analyze the impact of general economic determinants (see Table 2.1 and 2.2 for the specific determinants and the respective model parameters) on the land use pattern in general and the SRC coverage in particular. At this, we vary each general economic determinant individually, while all other parameters are kept constant. To quantify how sensitive the SRC expansion reacts to these determinants, we use the sensitivity index *SI* (see for example Bauer and Hamby (1991)) which is given by the percentage difference in model output when varying one parameter over its entire range:

$$SI = \frac{O_{max} - O_{min}}{O_{max}} \tag{2.11}$$

where O represents the model output. As we are interested in SRC expansion, we chose the SRC coverage Φ_{SRC} in year 50, i.e., the number of cells with SRC divided by total number of cells in the landscape, as investigated model output. As a result, a ranking of the relative importance of general economic determinants can be derived. As stated above, the standard deviation of the SRC coverage Φ_{SRC} and of the sensitivity index over the ensemble gives insights on the importance of the explicit spatial configuration. In addition, we test the transferability of the sensitivity results

Table 2.2: Overview of analysis steps: evaluation measures and model parameters investigated under different scenarios for which the single analysis steps are repeated.

Subject of analysis	**Evaluation measure**	**Investigated model parameters**	**Scenarios for transferability test**	**Section**
Step 1: General economic determinants	Sensitivity index of SRC coverage in landscape	Aggregated willingness to pay for SRC products D_{SRC}, Aggregated willingness to pay for annual crops D_{ANN}, Investment expenditures v, Recovery costs r, Harvest costs h, Transport price γ	a) Standard b) High discount rate c) High spatial correlation of soil	2.4.2
Step 2: Site-dependent determinants & interplay with general economic determinants	Probability of SRC occurrence	Aggregated willingness to pay for SRC products D_{SRC}, Aggregated willingness to pay for annual crops D_{ANN}	a) Standard b) High spatial correlation of soil	2.4.3

between landscapes with different aggregated spatial characteristics (high and low spatial correlation of soil quality) and between landscapes populated by farmers with different risk attitudes. Therefore, we repeat the gradual variation of general economic determinants for two more scenarios: a high discount rate of the agents and a high spatial correlation of soils.

In a second step, we analyze the impact of the two site-dependent determinants "soil quality" and "distance to processing plant". Therefore, we determine the probability that an agent in year 50 cultivates SRCs given a certain soil quality and distance to processing plant. The probability calculation is based on the ensemble of underlying landscapes. In addition, we analyze the interplay of the site-dependent determinants with general economic determinants by repeating the analysis for an increasing aggregated willingness to pay for the two agricultural products. Finally, we again test the transferability of this interplay between landscapes with different aggregated spatial characteristics of the underlying natural landscape (high and low spatial correlation of soil quality).

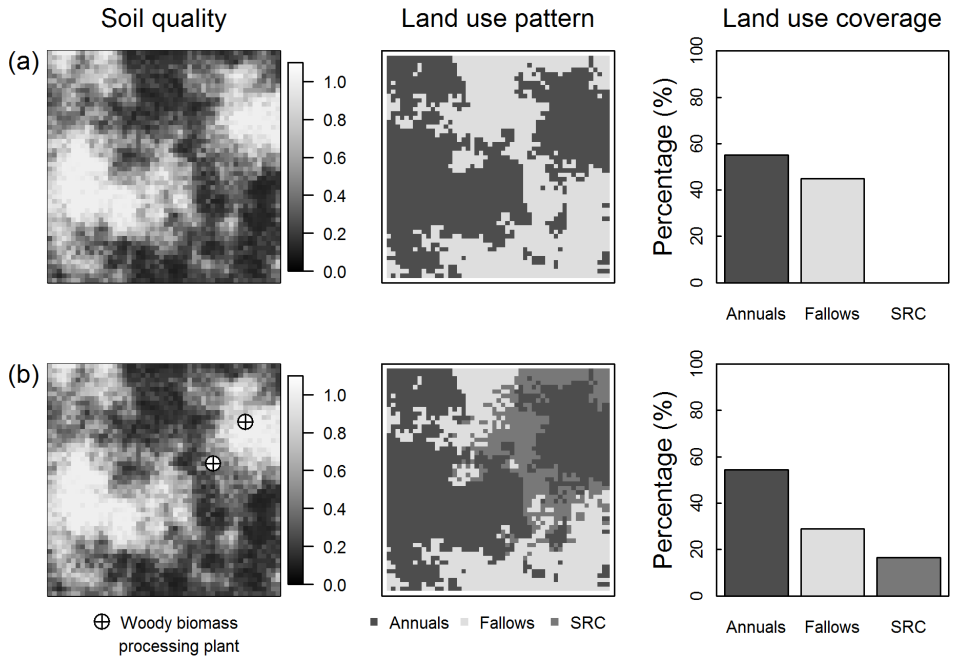

Figure 2.3: Underlying landscape of soil qualities and processing plants, resulting land use patterns and coverage of land use options after 50 years (a) without and (b) with SRC available as option.

2.4 RESULTS

2.4.1 *A new land use option enters the market*

For a better understanding of model dynamics, we first show land use patterns that emerge under the standard parameter set (see Appendix A). Here, we compare the case with and without SRC as land use option available (see Figure 2.3a,b respectively).

Without SRC (Figure 2.3a) as agricultural option, annual crops represent the dominant land use option with coverage of approximately 55% in this example and occupation of cells with high soil quality. The remaining 45%, characterized by low soil quality, are covered with fallow land. These sites are not chosen for agricultural production because here the yield of annual crops is low and agricultural practice hence not profitable. With SRC as land use option available (Figure 2.3b), 15% of the landscape is covered by SRC plantations at the expense of fallow land. The sites where SRC is cultivated are characterized by low transport costs to the woody biomass processing plants and by inferior soils. The reason for SRC cultivation on inferior soils is the low profit that annual crop cultivation yields on these sites. In the following section, we will investigate how different general economic determinants affect the expansion of SRCs.

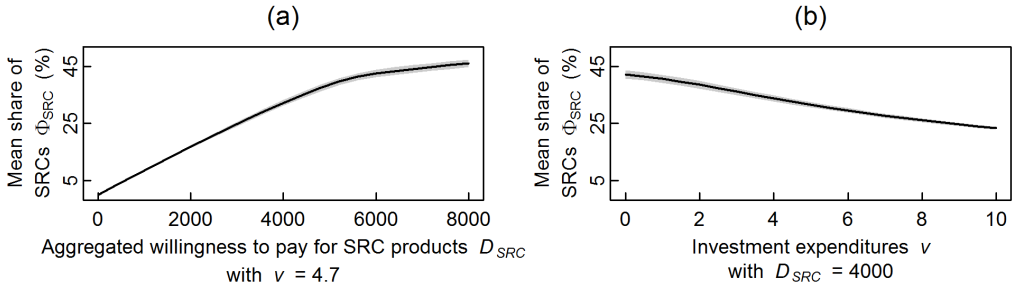

Figure 2.4: Mean SRC coverage Φ_{SRC} for increasing (a) aggregated willingness to pay for SRC products D_{SRC} and (b) investment expenditures v. Grey shading indicates the standard deviation over the ensemble of the low spatial correlation of soil qualities.

2.4.2 *Influence of general economic determinants*

In order to investigate the relative role of different general economic determinants, we analyze their impact on the mean SRC coverage Φ_{SRC} over the ensemble of landscapes with low spatial correlation of soil qualities.

Increasing aggregated willingness to pay for SRC products D_{SRC} as well as decreasing investment expenditures v positively affect the mean coverage of SRC plantations (see Figure 2.4a,b respectively). Triggered by a higher willingness to pay, the market price increases and positively influences the profit (see Equation 2.1 and 2.6). The other way around, high investment expenditures represent a hurdle, which hinders the SRC cultivation decision. Note the very low standard deviation (indicated by the gray shading in Figure 2.4) for the entire regarded parameter range. The landscapes within the ensemble only differ in their explicit spatial configuration. Therefore, the low standard deviation indicates that the explicit spatial configuration is not important for SRC coverage. Instead, the general economic determinants strongly affect the coverage of SRC plantations in the landscape and dominate the importance of the explicit spatial configuration.

In a second step, we quantified the impact of general economic determinants by performing a local sensitivity analysis and calculating sensitivity indices (for calculation see Equation 2.11). To test the relative importance of general economic determinants and the aggregated spatial characteristics of the underlying landscape, we performed the analysis for a) the standard scenario, b) a higher discount rate and c) higher spatial correlation of soil qualities. Thereby, we derive an indication whether general economic determinants would equally affect SRC expansion in different scenarios.

High sensitivity indices indicate a high impact of the corresponding determinant. Under the standard scenario, the main drivers of the SRC expansion are the aggregated willingness to pay for SRC products, the investment expenditures, and the harvest costs (see Figure 2.5a). The relative importance of these major determinants is especially influenced by the spatial correlation of soil quality (Figure 2.5c),

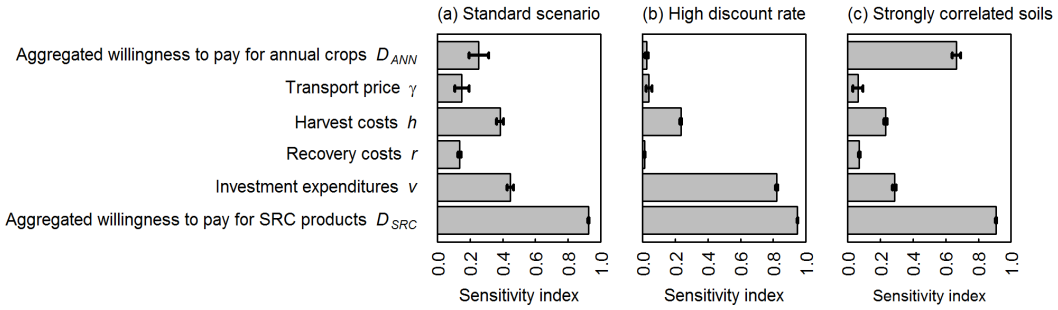

Figure 2.5: Sensitivity indices of SRC coverage to general economic determinants in the three scenarios: (a) standard, (b) higher discount rate and (c) higher spatial correlation of soils. Error bars indicate the standard deviation over the respective ensemble.

while the higher discount rate is only slightly influential (Figure 2.5b). Although the order of impact stays the same in the scenario with a high discount rate, the impact of investment expenditures strongly increases (see Figure 2.5b). With a higher discount rate, agents value profit accruing at the end of each rotation cycle less and therefore the initial hurdle of investment expenditures more strongly influences the SRC cultivation decision. Regarding landscapes with a different spatial structure, namely a higher spatial correlation of soil qualities, the relative importance of the different economic variables is changing. For instance, the impact of the aggregated willingness to pay for annual crops considerably increases (see Figure 2.5c). The reason for this lies in the distribution of soil qualities in the underlying landscape. While the spatial correlation of the distribution of soil quality is higher than that under the standard scenario, the mean soil quality is kept constant. As a consequence, the range of available soil qualities for the landscape with high spatial correlation of soil quality is narrower. The landscape contains fewer sites with low soil qualities. We assume that the productivity of annual crops is more decreased by low soil quality than that of SRCs. Therefore, fewer sites of low soil quality also imply fewer sites on which the yield of annual crops is very low and the cultivation of SRCs is therefore competitive. Therefore, the coverage of SRCs is more strongly dependent on the economic situation of the competitive land use option. Again, the explicit spatial configuration is not influential as standard deviations are low for all parameters and scenarios. Hence, the results are transferable to regions with the same aggregated spatial characteristics that differ only in their explicit spatial configuration.

2.4.3 *Influence of site-dependent determinants*

In the second step of the analysis (cf. Table 2.2), the attention is shifted to the spatial pattern of SRC occurrence, its determinants and the explanatory power of certain site-dependent determinants. The focus is on the relative importance of soil quality and the distance to woody biomass processing plants for SRC alloca-

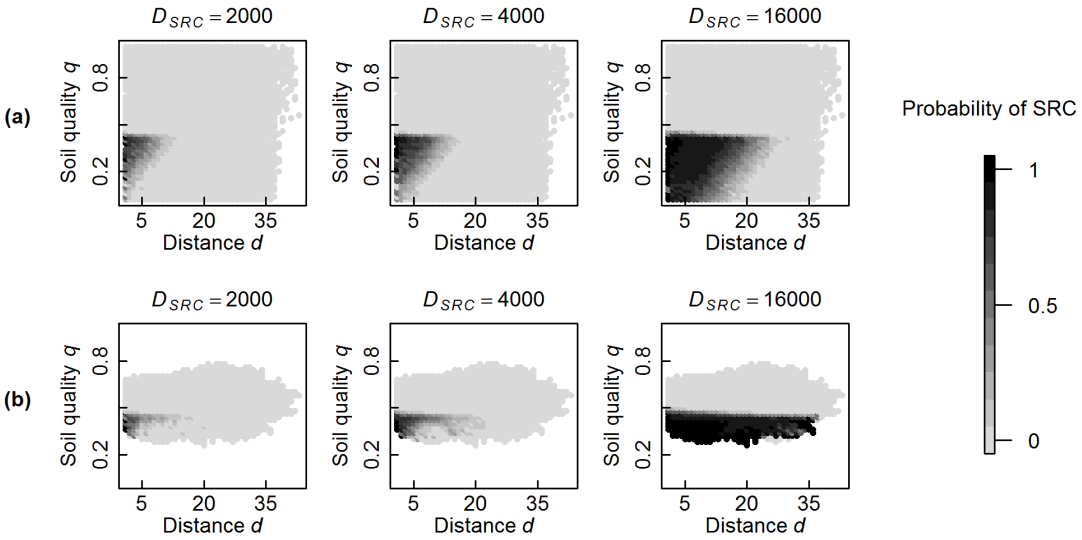

Figure 2.6: Probability of SRC occurrence for combinations of soil quality q and distance d present in the underlying landscapes for an increasing aggregated willingness to pay for SRC products D_{SRC} and scenarios (a) standard and (b) high spatial correlations of soil qualities.

tion, i.e., two attributes which are both site-dependent, heterogeneously distributed and known to influence yield and/or costs of the various options of crop cultivation under consideration. Additionally, we investigate the extent to which general economic determinants influence this relationship.

The probability of SRC occurrence is positively correlated to the soil quality, however, only up to a certain threshold of soil quality above which the probability decreases abruptly (see Figure 2.6). Higher soil qualities increase the yield of SRCs and therefore the probability of cultivating SRCs. However, on sites with very high soil qualities, the cultivation of SRCs is economically not competitive with the high yields of annual crops.

In most cases, higher distances to the processing plants d and therewith higher transport costs lead to a decreasing probability of SRC occurrence. Additionally, higher soil qualities often compensate for higher distances and, vice versa, lower distances for lower soil qualities (indicated by the triangle shape of high probabilities in Figure 2.6). Yield of SRCs, and therewith revenue, is higher on good soils. This compensates for higher transport costs of longer distances. Contrary, lower transport costs compensate for the lower revenue of SRCs on sites with lower soil quality.

But how does the aggregated willingness to pay for SRC products, D_{SRC}, as main general economic determinant affect the relative importance of site-dependent determinants for cultivation decisions? The distance of the chosen SRC sites to their next processing plants d varies with the aggregated willingness to pay for SRC prod-

ucts D_{SRC}. For an increasing D_{SRC} (left to right column), sites with considerably higher distances d become economically attractive and are therefore chosen for SRC cultivation. The higher willingness to pay leads to higher revenues from SRCs which compensates for higher costs of longer distances.

In contrast, the importance of soil quality as site-dependent determinant for SRC cultivation decision does not change with D_{SRC}. SRCs are cultivated on inferior - to medium-quality soils, independent of D_{SRC}. This is not a gradual interrelation. Instead, a threshold of soil quality can be identified above which the cultivation of SRCs is economically not competitive anymore. Hence, sites exist that are never chosen for SRC cultivation because of their site-conditions, independent of the main general economic determinant D_{SRC}.

Finally, we investigate how the aggregated spatial characteristic of the underlying landscape affects the results (i.e., the spatial correlation of soil quality; compare Figure 2.6a and b). Recalling, a higher spatial correlation leads to a narrower range of available soil qualities in the landscape. While we still find the same threshold of soil quality above which the probability of SRC occurrence drops to zero, the importance of distance changes. Under the scenario with highly correlated soil qualities, distance is only relevant for a low and a medium willingness to pay (Figure 2.6b). As described above, for higher correlated soil qualities, fewer sites with low soil qualities are available. This reduces the number of potential sites where SRC cultivation is competitive with annual crops. Therefore, farmers accept longer distances to processing plants. In other words, the comparison of the two scenarios indicates that the main general economic determinant D_{SRC} alters the importance of the site-dependent determinant "distance" for the SRC decision. While the distance is still influential for a high aggregated willingness to pay for SRC products D_{SRC} in the standard scenario, it is not in the landscape with high spatial correlation of soil qualities. Hence, the results are not fully transferable between landscapes with different aggregated spatial characteristics.

In addition to the impact of the aggregated willingness to pay for SRC products D_{SRC}, we assessed the aggregated willingness to pay for annual crops D_{ANN} (Figure 2.7). Again, higher distances to the processing plants d negatively influence the SRC occurrence probability. Moreover, as before, soil qualities and distances can compensate for each other (see explanation of Figure 2.6).

For a low willingness to pay for annual crops D_{ANN}, sites with high soil qualities are more likely to be chosen for SRC cultivation, independent of the spatial correlation of soil qualities (left column of Figure 2.7). Here, no competition with annuals takes place and SRCs are most profitable on good soils due to higher yields. As demand for annuals D_{ANN} increases, sites with low to medium soil qualities are chosen for SRC cultivation.

A high willingness to pay D_{ANN} also leads to an increase of the realized distance of the chosen SCR sites to the processing plants. Due to the advantageous situation of the competitive annual crops, only sites with lower soil qualities are chosen for SRC cultivation where yield of annual crops is low. These sites, however, can also

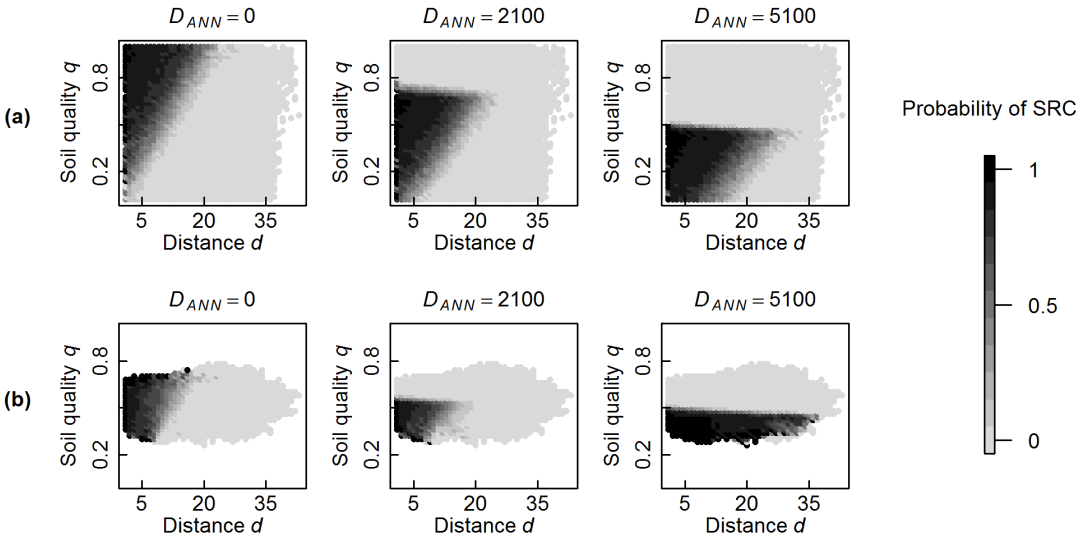

Figure 2.7: Probability of SRC occurrence for combinations of soil quality q and distance d present in the underlying landscapes for an increasing aggregated willingness to pay for annual crops D_{ANN} and scenarios (a) standard and (b) high spatial correlations of soil qualities.

be located far away from processing plants and therefore also these sites with long distances to processing plants are chosen for SRC cultivation.

The spatial structure of the underlying landscapes again influences the impact of distance: while distance is still influential for a high willingness to pay D_{ANN} in the standard scenario, it is not in the landscape with high spatial correlation of soil qualities. The impact of soil quality is again stable across the different spatial structures.

To summarize, the two considered general economic determinants D_{ANN} and D_{SRC} differently affect the importance of the site-dependent determinants "soil quality" and "distance to processing plants" for the SRC cultivation decision: while the distance is influenced by both general economic determinants, soil quality is only influenced by the aggregated willingness to pay for annual crops D_{ANN}. The way how the general economic determinants affect the importance of the site-dependent determinant "distance" differs between the two scenarios of underlying landscape structure. In contrast, the interplay of both general economic determinants and soil quality is the same for the two spatial structures. Hence, the derived insights on the interplay of general economic determinants and the site-dependent determinant "soil quality" are transferable between landscapes with different aggregated spatial characteristics, while the interplay of general economic determinants and the site-determinant determinant "distance" is not.

2.5 DISCUSSION

In this work, we assessed the relative importance of different economic and environmental determinants for agricultural cultivation choice and showed how these influencing factors might affect a possible SRC expansion in terms of the SRC coverage and their spatial distribution. In the following paragraphs, we will draw conclusions from our model results, discuss advantages of the applied method and finish with an outlook on future research.

2.5.1 *Determinants of SRC expansion*

2.5.1.1 *General economic determinants*

Our model results indicate that general economic determinants have a strong impact on the uptake of SRC practice. This effect is relatively stable across the investigated scenarios with differently structured landscapes and different risk attitudes of farmers:

i. Independent of the investigated scenarios (i.e., spatial correlation of soil quality and discount rate of farmers), the willingness to pay for SRC products showed to be the main economic determinant of SRC expansion. The reason is that the willingness to pay strongly affects the revenue of SRCs.

ii. Furthermore, investment expenditures, harvest costs and the willingness to pay for the competitive land use option “annual crops” represent strong determinants of SRC expansion. Thereby, the strength of their impact depends on the investigated scenario.

iii. Transport price and recovery costs have a relatively low impact under all investigated scenarios.

These results are in accordance with a study by Alexander et al. (2014) using an ABM to investigate SRC uptake in the UK. The authors showed large sensitivities for electricity prices and establishments grants. Furthermore, our results support insights from the empirical study of Mola-Yudego and Gonzalez-Olabarria (2010) in Sweden who revealed the importance of the demand for the spread of SRC cultivation. In a following empirical study, Mola-Yudego et al. (2014) additionally discuss the potential of establishment subsidies to promote SRC expansion.

In addition, we assessed to what extent these findings depend on the spatial structure of the underlying natural landscape. Therefore, we assessed the relevance of i. explicit spatial configurations and ii. aggregated spatial characteristics (i.e., the spatial correlation influencing the range of soil qualities present):

i. We showed that while general economic determinants have a strong impact on the SRC coverage, the importance of the explicit spatial configuration of the underlying landscape is negligible.

ii. In contrast, the range of soil qualities present in the landscape influenced the impact of the general economic determinants more strongly.

The results are therefore fully transferable between regions with different explicit spatial configurations, but are not between regions with different aggregated spatial characteristics.

2.5.1.2 *Relevance of site-dependent determinants*

In this study, we modeled farmers' crop cultivation decision using INCLUDE and were therefore able to analyze the impact of site-dependent determinants on the SRC cultivation decision. Our model results indicate that SRCs will be located on sites with low productivity in most cases as annual crops are economically more competitive on sites with higher soil quality. This is confirmed by a survey amongst SRC operators in Bavaria in which SRC sites show below-average land rents (Hauk et al., 2014). Skevas et al. (2016) showed a reduced difference in revenue between corn and bioenergy perennials on poor soils. Similarly, Helby et al. (2004) revealed a slight economic disadvantages for SRCs over food production on good soils. However, we showed that an intense decrease in the willingness to pay for annual crops will lead to a reallocation of SRCs to sites with higher soil quality. Mola-Yudego and Gonzalez-Olabarria (2010) also empirically showed a trend in SRC movement to areas with higher production. Our study suggests that this is only possible when the demand for the production of annual agrarian products is low.

In our model, sites chosen for SRC cultivation are characterized mostly by low soil qualities. Therefore, direct conflicts with food production are negligible since yields of annual crops would be low on these sites. This is in line with Aust et al. (2014): the authors argued that SRC on marginal agricultural land will only slightly affect food and feed production due to low yields on these sites. Similarly, various studies promote the use of marginal land as option to reduce competition with food production (Fitzherbert et al., 2008; van Dam et al., 2009; Hartman et al., 2011). On the other hand, areas with low soil quality may possess high ecological value (e.g., in the case of grasslands (cf. BfN, 2012)). In our model, we do not explicitly model the ecological value of sites. However, if land has been left fallow before the SRC expansion, it might have potentially built up ecological value.

The influence of the site-dependent determinant "distance to the processing plants" was found to be more sensitive to general economic determinants such as the aggregated willingness to pay for SRC products and for annual crops, respectively. At this, we identified situations ranging from a high impact of distance - with only sites close to processing plants being chosen for SRC cultivation - up to no impact of distance on SRC cultivation decision.

2.5.1.3 *Policy implications for promoting SRCs*

Currently, two main policy instruments to promote SRC expansion are applied in Germany. First, investment subsidies exist in some federal states and differ with respect to design (Strohm et al., 2012; Peschel and Weitz, 2013). They are important to overcome the barrier of high initial investment costs and to reduce the risk of investment (e.g., Faasch and Patenaude, 2012; Strohm et al., 2012; Wolbert-Haverkamp and Musshoff, 2014). This is also supported by one of our model results: the high impact of investment expenditures. Therefore, it would be valuable to improve the subsidy design and provide coordination and harmonization of investment subsidies: requirements regarding minimal investment amount and minimal number of trees should be adjusted to allow for participation of small plantations and lower participation barriers (Strohm et al., 2012). Secondly, as of late, SRC can be accounted for as an ecological focus area under the Greening component of the European Common Agricultural Policy (CAP) (Finger, 2016).

Further proposed instruments include the support of networks between SRC suppliers and demand side actors, support for research and development and information instruments (Strohm et al., 2012). Additionally, in some studies, setting minimum wood chip prices through supply contracts are named as a measure to reduce investment uncertainty (Ridier et al., 2012; Wolbert-Haverkamp and Musshoff, 2014).

However, guaranteeing minimum wood chip prices or wood-specific quotas by public support instruments might cause market actors to choose cheapest wood or biomass resources available, not necessarily SRCs. Therefore, a very technology- and feedstock-specific design of support instruments would be required to incentivize SRCs (e.g., a higher substrate tariff class for SRCs as implemented in the German Renewable Energies Act (EEG) 2012). However, attempting to incentivize SRC specifically through demand-sided, sectoral deployment support has high risks for steering errors. Large scale SRCs may be incentivized if demand resulting from policy instruments is high enough, but it may end up not to be a competitive feedstock compared to other biomass resources nor a competitive climate change mitigation option. This would result in high public costs of errors as it was for example seen for the "NaWaRo bonus" (renewable raw material bonus) in earlier versions of the EEG (cf. Britz and Delzeit, 2013). In addition, decisions about the sectoral use of SRC wood would be distorted in favor of energetic applications as long as comprehensive bioeconomy policies are absent.

When assessing the appropriateness of policy instruments, it is important to consider that environmental benefits of SRCs strongly depend on site- and plantation-specific characteristics (e.g., tree species, cultivation design) and that negative impacts are also possible (e.g., Dauber et al., 2010; Thrän et al., 2011; Strohm et al., 2012). If SRC were supported through a demand-sided deployment support instrument, this would need to be complemented by specific spatial explicit environmental requirements or SRC-specific sustainability certification standards. This would en-

sure a positive environmental balance, but also increase complexity and transaction costs of demand-sided interventions.

We conclude that investment subsidies in combination with information, networking, and research and development support seem to be the most promising approach to reduce barriers posed by high initial investment requirements, but should be combined with environmental minimum requirements (cf. Thrän et al. (2011) or Strohm et al. (2012)). These subsidies would be only viable for the market entry phase to generate learning effects and should be phased out eventually. Income stream risks would already be reduced by providing consistent and reliable political framework conditions, which increase planning security about future demand for woody biomass. Reliable framework conditions encompass general reliability of signals from sectoral bioenergy policies (e.g., in Germany the EEG in the electricity sector or the Renewable Heat Act (EEWärmeG) and the Market Incentive Programme in the heating sector), but also from biofuel policies (for innovative applications, e.g., wood gasification) and bioeconomy policies. In this respect, energy prices and prices of fossil fuel substitutes are affected by the EU Emissions Trading System and energy taxation.

In general, the effectiveness increases with increasing specificity of intervention (ranging from instruments directed at renewable energy in general over wood in general to SRC-specific instruments), but so does the risk of inefficiency and market distortions. Whether SRC emerges as a competitive resource option should therefore be left to market actors, to reduce distortions of land, energy and material biomass markets.

2.5.2 *Advantages of the applied methodology*

The cultivation of perennial energy crops, such as SRCs, resembles a long-term investments decision (Skevas et al., 2016). Modeling SRC cultivation decisions therefore requires incorporating different time scales and risk attitudes. We use approaches from investment theory which allow the comparison between land use options with different lengths of harvest cycles.

The chosen method of using stylized landscapes enables us to derive a general understanding beyond a specific region. Furthermore, the use of a landscape generator for the underlying landscape enables us to test the transferability of results between landscapes. We generate an ensemble of initial landscapes with fixed aggregated statistical characteristics (termed geostatistical model by Jager et al. (2005)). Model evaluation was then performed using statistics over the entire ensemble. Besides statistically significant results (Dibble, 2006), this also enables the investigation of the relevance of explicit spatial configuration by quantifying the variation in model predictions due to variation in spatial structure (as proposed as spatial uncertainty analysis by Jager et al. (2005)).

Furthermore, the approach enables to test the transferability of results between landscapes with different aggregated spatial characteristics. Not only different explicit spatial configuration can be simulated but also aggregated spatial characteristics, such as spatial correlation of soil qualities, can be controlled with the landscape generator. This enables us to investigate different landscape types, a strength not supported by studies based on real landscapes (Everaars et al., 2014).

The low variation within ensembles shows that our results are generalizable for regions with different explicit spatial configuration, given the premises of similar aggregated spatial characteristics. Generalizability of ABMs over wider regions is of increasing importance because this can facilitate to couple them with complex environmental models (Brown et al., 2016). This is especially important, when investigating novel land use practices for which data on large commercial plantations is missing. Immerzeel et al. (2014, p. 205) state the research need for "accurate projection of future distribution of energy crops" that are currently hampered by limited information due to low acreage. Holland et al. (2015) and Milner et al. (2015) highlight the importance of scaling-up feedstock production across landscapes in order to assess impacts of second generation feedstocks on ecosystem services. Our model can remedy this by explicitly reflecting farmers' decision-making under potential future economic and policy scenarios.

2.5.3 *Outlook*

In this study, we assumed rational profit maximization to be close to established economic theory. However, also non-economic factors are believed to influence agricultural decisions. For example, several empirical studies on farmers' behavior showed that ecological awareness might play a role (Karali et al., 2013; Brändle et al., 2015; Swinton et al., 2016). In this respect, INCLUDE provides a reference model that could be enhanced in future research by including also non-economic influence factors of decisions.

Despite known environmental benefits of SRCs, negative effects of SRCs have been described (Fletcher et al., 2011; van der Hilst et al., 2012; Immerzeel et al., 2014). Therefore, an thorough environmental impact assessment of SRCs is needed (cf. Holland et al., 2015). Our approach of modeling land use decisions can contribute to this research need by enabling to assess environmental effects of a possible SRC expansion on the regional scale.

To conclude, by assessing different general economic and site-dependent determinants of SRC cultivation decisions this study gave insights on barriers of a possible SRC expansion. The identification of determinants with strong impacts, such as investment expenditures or the willingness to pay for SRC products, can be taken as starting point for the future design of effective government interventions to promote SRCs in order to meet in a sustainable way an increasing demand for wood, especially in the context of a worldwide politically fostered bioeconomy. The analysis

suggests that investment subsidies might be a promising approach to promote SRCs, but should be combined with environmental minimum requirements.

3

ASSESSING REGIONAL-SCALE IMPACTS OF SHORT ROTATION COPPICES ON ECOSYSTEM SERVICES BY MODELING LAND USE DECISIONS

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3.1 ABSTRACT

Meeting the world's growing energy demand through bioenergy production involves extensive land use change which could have severe environmental and social impacts. Second generation bioenergy feedstocks offer a possible solution to this problem. They have the potential to reduce land use conflicts between food and bioenergy production as they can be grown on low quality land not suitable for food production. However, a comprehensive impact assessment that considers multiple ecosystem services (ESS) and biodiversity is needed to identify the environmentally best feedstock option, as trade-offs are inherent. In this study, we simulate the spatial distribution of short rotation coppices (SRCs) in the landscape of the Mulde watershed in Central Germany by modeling profit-maximizing farmers under different economic and policy-driven scenarios using a spatially explicit economic simulation model. This allows to derive general insights and a mechanistic understanding of regional-scale impacts on multiple ESS in the absence of large-scale implementation. The modeled distribution of SRCs, required to meet the regional demand of combined heat and power (CHP) plants for solid biomass, had little or no effect on the provided ESS. In the policy-driven scenario, placing SRCs on low or high quality soils to provide ecological focus areas, as required within the Common Agricultural Policy in the EU, had little effect on ESS. Only a substantial increase in the SRC production area, beyond the regional demand of CHP plants, had a relevant effect, namely a negative impact on food production as well as a positive impact on biodiversity and regulating ESS. Beneficial impacts occurred for single ESS. However, the number of sites with balanced ESS supply hardly increased due to larger shares of SRCs in the landscape. Regression analyses showed that the occurrence of sites with balanced ESS supply was more strongly driven by biophysical factors than by the SRC share in the landscape. This indicates that SRCs negligibly affect trade-offs between individual ESS. Coupling spatially explicit economic simulation models with environmental and ESS assessment models can contribute to a comprehensive impact assessment of bioenergy feedstocks that have not yet been planted.

3.2 INTRODUCTION

The world's energy demand is continuously growing (IEA, 2010; Chum et al., 2011). Meeting this demand through bioenergy production involves extensive land use change which could have serious environmental and food security implications (Tilman et al., 2009, p. 318). For example, bioenergy expansion could negatively affect biodiversity (Fitzherbert et al., 2008) or cause indirect land use change (Lambin and Meyfroidt, 2011). One possible solution to this problem are second generation (2G) bioenergy feedstocks: "perennial, ligno-cellulosic feedstocks that are non-food crops" (Milner et al., 2015) promoted by the EU through the Renewable Energy Directive (EU RED) (Holland et al., 2015). They may reduce conflicts with food

production as they can be grown on low quality land that is unsuitable for food production (Valentine et al., 2012). However, science-based safeguards need to be put in place to ensure that the best feedstocks for avoiding negative social and environmental impacts are exploited for bioenergy production (Tilman et al., 2009). In the process, trade-offs between provisioning and regulating ecosystem services (ESS) (i.e., human benefits from the ecosystem (Hassan et al., 2005)) need to be evaluated (Power, 2010; Raudsepp-Hearne et al., 2010; Werling et al., 2014). Therefore, a comprehensive impact assessment of 2G feedstocks considering multiple ESS is required. In temperate climate zones, short rotation coppices (SRCs) are prominently discussed 2G feedstocks (Hastings et al., 2014).

SRCs are fast-growing trees, in the EU mostly poplar and willow species, which are partly commercially grown as perennial energy crops on agricultural land (Njakou Djomo et al., 2015). Plantations are harvested every 3–9 years and afterwards stump sprouting takes place. After several of these rotations, the land is re-cultivated. SRCs may fulfill multiple bioeconomic purposes: they serve as a material source and feedstock for heat and electricity generation. At the same time, SRCs are thought to increase biodiversity (Holland et al., 2015; Sage et al., 2006; Rowe et al., 2011) and positively affect soil and water quality (Makeschin, 1994; Schmidt-Walter and Lamersdorf, 2012). Furthermore, under the reformed Common Agricultural Policy (CAP) (2014–2020) farmers receiving subsidy payments are obliged to reserve at least 5% of their arable land for ecological focus areas (EFAs). SRCs are regarded as EFAs due to their beneficial impacts on the environment (Pe'er et al., 2014). Despite the expected environmental benefits, currently only approximately 6500 ha SRCs are established in Germany (Drossart and Mühlenhoff, 2013). However, Kraxner et al. (2013) project a worldwide increase in SRC plantations to 190–250 million ha by 2050.

Several studies have modeled the potential supply of perennial energy crops and the accompanying impacts (e.g., Schmidt-Walter and Lamersdorf, 2012; Meehan et al., 2013; Aust et al., 2014; Tölle et al., 2014). Thereby, it is crucial to consider the spatial configuration of energy crops in ESS assessments (Asbjornsen et al., 2014). Holland et al. (2015) and Milner et al. (2015) emphasize the need to conduct assessments on commercial scale feedstock production systems. SRCs are currently seldom implemented and therefore empirical data on the spatial allocation of SRCs is missing. Models simulating upscaling processes therefore use heuristics to allocate new land use options such as SRCs in the landscape. Meehan et al. (2013), for example, replace annual with perennial energy crops. Tölle et al. (2014) allocate SRCs on land with suitable cultivation conditions (e.g., sufficient available soil water capacity). Scenarios that reflect farmers' decisions within the existing and potential future political framework are needed. Based on these scenarios, more realistic spatial allocations of SRCs can be determined. Several studies have shown that it is important to include human decision-making in models (Parker et al., 2008; Le et al., 2012).

In this study, we use a spatially explicit economic simulation model to simulate farmers' decisions about their agricultural activity, such as the cultivation of a certain crop (SRC or conventional annual crops). While the farmers decide according to their individual cultivation conditions (biophysical cultivation conditions, transport costs), endogenous markets mediate interactions among them. With this model, we investigate four economic scenarios differing in the demand for SRC products. These scenarios reflect the maximum range of outcomes, which thereby more likely comprise the actual future of SRC deployment. Embedded in the recent discussion on "Greening" in Germany (Lupp et al., 2014), we also assess two policy scenarios where a certain share of the landscape is used for cultivating SRCs to fulfill the CAP requirements. We apply the model to the Mulde watershed in Central Germany. At this regional scale, we assess the impact of SRC expansion on crop yields, carbon storage, nutrient and sediment retention, as well as biodiversity by using the environmental and ESS assessment models InVEST and GLOBIO. We cover these local/regional ESS as those are seldom included in common environmental assessments of bioenergy feedstock production, e.g., LCAs (Meyer and Priess, 2014; Koellner and Geyer, 2013). Overall, we simulate land use maps of SRC production and quantify ESS synergies and tradeoffs resulting under different economic and policy-driven scenarios at the regional scale. The study aim is to derive general insights and mechanistic understanding of ecosystem service impacts of large-scale SRC deployment and to visualize some potential futures for SRC deployment.

3.3 METHODS AND MATERIALS

In this study, we combine a spatially explicit economic simulation model with environmental and ESS assessment models to assess the impact of land use decisions on provisioning and regulating ESS and biodiversity. In the first part of the analysis, we use the economic simulation model to generate land use patterns for a specific case study under different economic scenarios. Thereby, we assess a range of outcomes, which more likely comprise the actual future of SRC deployment. In the second part of the analysis, we use environmental and ESS assessment models InVEST and GLOBIO to assess ESS supply in a spatially explicit way. Here, we apply this modeling framework to the expansion of SRCs as 2G feedstock in the Mulde watershed in Central Germany.

3.3.1 *Study site*

The study area is part of the Mulde watershed, which is mostly located in the German federal state of Saxony (see Figure 3.1), covering an area of about 5 791 km^2. The Mulde is a tributary of the Elbe river formed by its headwaters Zwickauer Mulde and Freiberger Mulde, which have their source in the Ore Mountains. Its altitude ranges from 70 to 1 214 m. We modeled SRC deployment and ESS for the reference

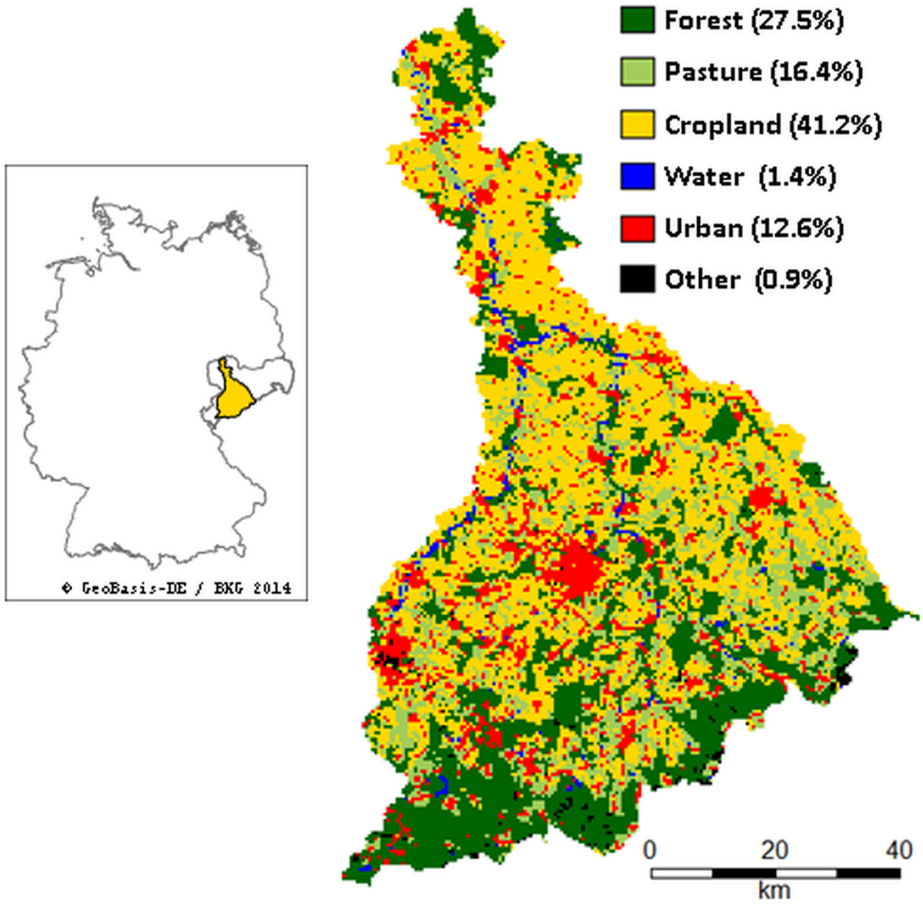


Figure 3.1: Land use/land cover in the Mulde watershed and its location in Germany (EEA, 2013; Wochele et al., 2014; Wochele-Marx et al., 2015).

year 2006, for which major land use/land cover (LU/LC) data is available. Climatically, the precipitation in 2006 in the Mulde watershed with its humid continental climate (834.6 mm, SD: 180.6 mm) was 9% lower than the normal climate conditions for the period 1991 to 2011 (Jäckel et al., 2012); the minimum and maximum average temperatures in 2006 in the Mulde watershed (T_{min}: 4.5°C, SD: 0.8°C, T_{max}: 13.1°C, SD: 1.4°C) deviated less than 1°C from normal climate conditions for the period 1991 to 2011 (Jäckel et al., 2012). The amplitude of precipitation ranged between 500 mm and 1290 mm in 2006. The loess soils in the lowlands are dominated by crop production, whereas the Ore Mountains are dominated by forestry (Altermann and Ruske, 1997). Winter wheat (24%), winter rapeseed (18%), and winter barley (12%) dominated the cropland in 2006. Currently, SRCs account for only 0.03% of the agricultural land in Saxony (AgroForNet, 2013). There are only a small number of SRC sites in the Mulde watershed, most of which are trial sites. In contrast, there are about 36 combined heat and power (CHP) plants in Saxony (Das

et al., 2012) that may use SRC products. Fifteen of these CHP plants are located in the Mulde watershed.

3.3.2 *Economic simulation model*

The spatially explicit model depicts land use decisions of multiple profit-maximizing farmers who interact via an economic market. The model is an extended version of the model described in Weise (2014). Here, we present a short description of the model; the full model description using the ODD+D protocol (Müller et al., 2013) can be found in Appendix B. The ODD+D extends the widely used Overview, Design Concepts and Detail (ODD) protocol (Grimm et al., 2006, 2010) by including the description of human decision-making.

The landscape of the Mulde watershed is subdivided into pixels. Each cropland pixel (Wochele et al., 2014; Wochele-Marx et al., 2015) was assigned to an individual land user (agent). The underlying landscape consisted of a soil quality layer (LfULG, 2012) and the sites where consumers of SRC products, i.e., CHP plants, were located (Das et al., 2012). The agent cultivated land to generate income through the production of agricultural goods. The agent could choose between three different land use options: SRCs, annual crops, or fallow land. Among these, the agent chose the land use option that would yield the maximum net profit. The net profit for a land use option was given by the difference between revenue and costs. The revenue was influenced by market prices and the site-specific yield, while the costs were incorporated via production and transportation costs. The yield was determined by biophysical site-conditions, i.e., soil quality, while transportation costs of SRC products depended on the distance to CHP plants. Although traditional and self-interested profit maximization (i.e., the rationale of homo economicus) is widely accepted as a decision criterion in economics, non-commercial factors are also believed to influence agricultural decisions (Renting et al., 2009). However, Brown et al. (2016) show with a survey in the UK that economic factors are of primary importance. Non-economic factors such as the willingness to reduce GHG emissions are less important; they only slightly influence decisions to cultivate bioenergy crops. Therefore, we see this simplification as appropriate for our model design. For SRC practice in Germany, farmers are provided with advisory material (e.g., the manual of Skodawessely et al. (2010) or the profitability calculator provided by the AGROWOOD research project (AGROWOOD, 2015)). To reflect the situation in practice, we adapted the profitability calculation suggested therein as a decision criterion.

Market prices for wood chips from SRCs and for annual agricultural products were given by the balance of exogenously given demand and the endogenously resulting supply that was determined by the agents' decisions. Agents interacted indirectly via the resulting market price, i.e., agents reacted to market prices and these market price were determined by the decisions of all agents. This price formation on the

market is in line with standard economic theory (e.g., equilibrium concept; cf. Engelkamp and Sell (2007) or Mankiw and Taylor (2006)). Thereby, we incorporated the critical market feedback of supply decisions that result in price changes which influence again supply decisions (as also used by Lawler et al. (2014)). We assumed that the market price was equivalent across all CHP plants and was determined by the joint supply from all agents (termed "regional price"). Besides utilizing SRC products, CHP plants were assumed to distribute resources: plants with a high supply (higher as their own capacity) might transport and sell to another plant or other customers. However, we tested this scenario against a second scenario in which the market price was formed for each of the CHP plants and was determined by the amount of SRC that was sold to a specific plant (termed "local price"). Here, market prices might vary between plants. The two investigated price scenarios represent two extremes at opposite poles of a spectrum. Simulated land use patterns and the regional ESS showed to be mostly equivalent across both price scenarios, cf. Table C.1 and C.2 in the appendix. Hence, it is unlikely that the actual land use patterns and ESS supply differ substantially from these two conceptual extremes. Here, we focus on the "regional price" scenario and show results for the "local price" scenario in Appendix C.

The majority of parameters in the economic model were based on the literature (for details see full model description in Appendix B). The demand for annual agricultural crops was calibrated using the LU/LC data for the Mulde watershed. This demand was set by aligning the initial shares of land use options under the baseline scenario with the empirical ones in the Mulde watershed.

3.3.3 *Scenarios for SRC development*

For the standard scenario, we assumed that the CHP plants currently present in the Mulde watershed were the only consumers of wood chips and that their biomass demand was fully met by wood chips from SRCs. We calculated the share of SRCs needed to meet the demand of existing CHP plants in the Mulde region by using the reference values from the FNR (FNR, 2013) as a basis. Using this information, we parameterized the demand for SRC products in the economic simulation model so that the required SRC share was provided in the modeled region.

Increasing global demand for wood combined with limited forest resources will most likely increase prices for wood in the future (Matzenberger et al., 2015). Therefore, we assessed the impact of an increasing demand for wood chips by comparing the standard scenario with three further scenarios (medium, high and very high demand). In these additional scenarios, we did not spatially allocate additional CHP plants in the landscape because the regional energy and heat demand is unlikely to increase further. We rather expected that other than energetic uses in CHP plants (e.g., material use) increased the regional demand for wood resources (Becker and Brunsmeier, 2013). This is in line with (Edel and Thrän, 2012), who identified a

likely solid biomass supply deficit in Germany that could be partly filled with SRCs. To depict this in the economic model, we increased the demand for SRC products over the different scenarios and modeled SRC production for other regional uses. Thereby, we assumed that the existing CHP plants acted as trading centers and that farmers delivered SRC products to the already established infrastructures. By considering this range of demand for SRC products, we aimed at investigating the maximum variation in biodiversity and ESS supply that might be caused by expanding SRC production. The actual outcomes will then likely be bounded by this range.

In addition to the economic scenarios, we included two policy scenarios. Embedded in the recent discussion on "Greening" in Germany (Lupp et al., 2014), we assumed that 16.67% of the entire arable land is used for cultivating SRCs. Under the recent CAP reform, farmers need to implement EFAs on 5% of their land to receive payments. One of many options is to plant SRCs. However, SRCs are weighted less (weighting factor: 0.3) than set-aside land (weighting factor: 1). Hence, 16.67% (= 5%/0.3) of land needs to be used for SRC cultivation. Again, we investigated two extremes to gain understanding on the range of possible outcomes of this policy intervention. In the first policy scenario, we assumed that SRCs would be allocated to land with low soil quality for economic reasons. We assumed potential deficiencies of this policy measure (i.e., EFAs) due to the freedom of location choice for farmers. Therefore, we compared this scenario to a second policy scenario where the best 16.67% of the entire arable land with respect to soil quality would be converted to SRCs to analyze potential ESS impacts.

3.3.4 *Ecosystem services and biodiversity*

3.3.4.1 *Provisioning ecosystem services*

For all scenarios, we calculated the crop and SRC yields. For crop production, we spatially downscaled the average yield per ha at the district level (StaLa Sachsen, 2007; TLS, 2007). We considered the impact of soil and climatic heterogeneity on yields by calculating the arithmetic mean of the agricultural yield potential for each district (BGR, 2014). We assigned each pixel the yield available at district level and raised or lowered this value depending on the actual agricultural yield potential of the pixel relative to the district arithmetic mean.

We selected the SRC species poplar due to the dry climate in the agriculturally dominated lowlands. To model a spatially explicit SRC yield, we used the regression model developed in Saxony by Ali (2009):

$$Yield = a_4 \cdot \left(a_1 \cdot C + a_2 \cdot P \cdot SQI + a_3 \cdot \frac{T}{AWC} \right)^{a_5} \tag{3.1}$$

with $$a_4 = -1.13 \cdot 10^{-9} \cdot N^2 + 2.54 \cdot 10^{-5} \cdot N + 0.028 \tag{3.2}$$

and $$a_5 = 3.41 \cdot 10^{-9} \cdot N^2 - 5.01 \cdot 10^{-5} \cdot N + 2.614 \tag{3.3}$$

where C is the rotation cycle, P the sum of precipitation for the months May and June, SQI the soil quality index, T the average temperature for the months April until July, AWC the available water holding capacity, N the planting density and a_1 up to a_5 are species-specific parameters. Based on the existing practice in Saxony, we assumed the use of the most common poplar clone Max with the parameters and datasets given in Table 3.1.

Table 3.1: Parameter and datasets used to calculate yield of the poplar clone Max.

	Item	**Value**	**References**
N	Planting density [n ha^{-1}]	9446	AgroForNet (2013)
C	Rotation cycle [a^{-1}]	5.5	AgroForNet (2013)
a_1		1.569	Ali (2009)
a_2		0.0004	Ali (2009)
a_3		-23.198	Ali (2009)
P	Precipitation (sum May-June) [mm]		Jäckel et al. (2012)
T	Average temperature April-July [°C]		Jäckel et al. (2012)
SQI	Soil quality index		LfULG (2012)
AWC	Available water holding capacity [mm]		LfULG (2012)

3.3.4.2 *Regulating ecosystem services and biodiversity*

We used InVEST (Integrated Valuation of Environmental Services and Tradeoffs) to calculate different regulating ESS. InVEST uses ecological production functions to simulate the provision of ESS under different scenarios. First, we calculated the amount of carbon stored according to the IPCC guidelines (Eggleston et al., 2006), supported by InVEST (Nelson et al., 2009; Kareiva et al., 2011), with the data indicated in Table 3.2 for 2006. Second, we modeled the phosphorous (P) export and retention with InVEST. Based on the runoff, the P inputs were routed through the watershed. The retention largely depends on the topography and vegetative cover. Third, we modeled the amount of retained sediment with InVEST based on the universal soil loss equation (Sharp et al., 2013; Wischmeier and Smith, 1978). The baseline scenario for P and sediment retention was validated in Meyer et al. (2016). Furthermore, we assessed impacts on biodiversity with GLOBIO as described in Alkemade et al. (2009). We modeled the impact of major drivers of biodiversity loss (i.e., land use change, habitat fragmentation, population density, infrastructure expansion and atmospheric N deposition) on the mean species abundance (MSA) existing in undisturbed ecosystems. A completely undisturbed ecosystem would have an MSA of 1, the lowest MSA is 0; SRCs have a value of 0.2.

Table 3.2: Data items for carbon storage (No. 2, 16), P retention and export (No. 1–7, 10–12), sediment retention and export (No. 1–3, 8–9, 13–15 and for biodiversity (No. 2, 17–21); we refined the default parameter of InVEST with the indicated sources (No. 10–15); methodological sources are equally included.

	Input datasets	**References**
1	DEM (3 arc-seconds) [m]	Lehner et al. (2008)
2	LU/LC	EEA (2013); Wochele et al. (2014); Wochele-Marx et al. (2015)
3	Potential Natural Vegetation	LfULG (2011)
4	Reference Evapotranspiration (10 arc-min) [mm a^{-1}]	FAO Geonetwork (2014)
5	Precipitation [mm a^{-1}]	Jäckel et al. (2012)
6	Depth to any soil restrictive layer [mm]	Panagos et al. (2006); LfULG (2012)
7	Available water holding capacity [cm cm^{-1}]	Panagos et al. (2006); LfULG (2012)
8	Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	Bräunig (2013)
9	Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	LfULG (2012); Bischoff (2014)
10	Rooting depth [mm]	
11	P export [kg ha^{-1} a^{-1}]	Reckhow et al. (1980)
12	P retention efficiencies [%]	
13	cover-management factor (C)	
14	Support practice factor (P)	BSMUL (2013)
15	Vegetation sediment retention efficiency [%]	
16	Carbon pools [t ha^{-1}]	Fraver et al. (2002); Bohn et al. (2005); Müller-Using and Bartsch (2009); Wördehoff et al. (2011); Polley and Henning (2012); Strogies and Gniffke (2012); BGR (2013)
17	Population density [n km^{-2}]	Priess (2016); Priess et al. (under review)
18	Street and railway map	BKG (2014)
19	N deposition	Builtjes et al. (2011)
20	Critical N loads	Builtjes et al. (2011)
21	Terrestrial ecoregions	Olson et al. (2001)

3.3.4.3 *SRC impacts on regulating ESS bundles*

We used cluster analysis to identify ESS bundles based on methods described in Mouchet et al. (2014). ESS bundles are described as "sets of services that appear together repeatedly" by Raudsepp-Hearne et al. (2010, p. 5242). Pixels in our landscape were clustered into bundles of similar ESS supply and the frequency of each bundle over the entire landscape was recorded. We identified ESS bundles by K means and displayed them as starplots in R (R Development Core Team, 2009).

In a second step, we applied a binomial logistic regression model. This approach gives insights on the factors that distinguish the occurrence of different bundles. In the regression model, we tested indicators of landscape composition and naturalness, soil, topography, and climate, see Table D.1 in Appendix D. We calculated landscape composition and naturalness indicators in a moving window approach for a buffer radius of 5 km, which was ten times the LU/LC pixel size. We removed variables with variance inflation factors >10 to reduce multicollinearity. Next, we removed non-significant explanatory variables in a backward stepwise manner based on the Akaike information criterion. Next, the significance of the final model was tested against a null model using a likelihood ratio test. To assess the spatial autocorrelation of the final model, we added geographic coordinates and tested for significant difference towards the final model without geographic coordinates with the likelihood ratio test.

3.4 RESULTS

3.4.1 *SRC distribution and associated ecosystem services impacts under economic and policy-driven scenarios*

Spatial distribution of SRCs depended on the economic and policy-driven scenarios (Figure 3.2). The share of SRCs differed substantially between the four economic scenarios (2%, 4%, 14%, and 24% of the total area for standard, medium, high, and very high demand, respectively). However, SRC distributions showed similar characteristics under the four scenarios: sites with high soil quality indices showed hardly any deployment. SRCs are only economically viable on inferior soils, where they can compete with annual crops. Distribution of SRCs under the first policy-driven scenario, where 16.67% of agricultural land with the lowest soil quality indices was converted to SRC cultivation (see scenario 5), was largely similar to the economic scenario with high demand.

In general, economic and policy-driven scenarios affected provisioning and regulating services as well as biodiversity (Figure 3.3). Scenario 1 (standard demand) (i.e., demand from the currently existing CHP plants solely met by SRCs) did not have a substantial effect on the investigated ESS. Only a large increase in demand (scenarios 3 and 4) for woody products from SRCs revealed substantial trade-offs between the provision of annual agricultural products and SRC yields as well as

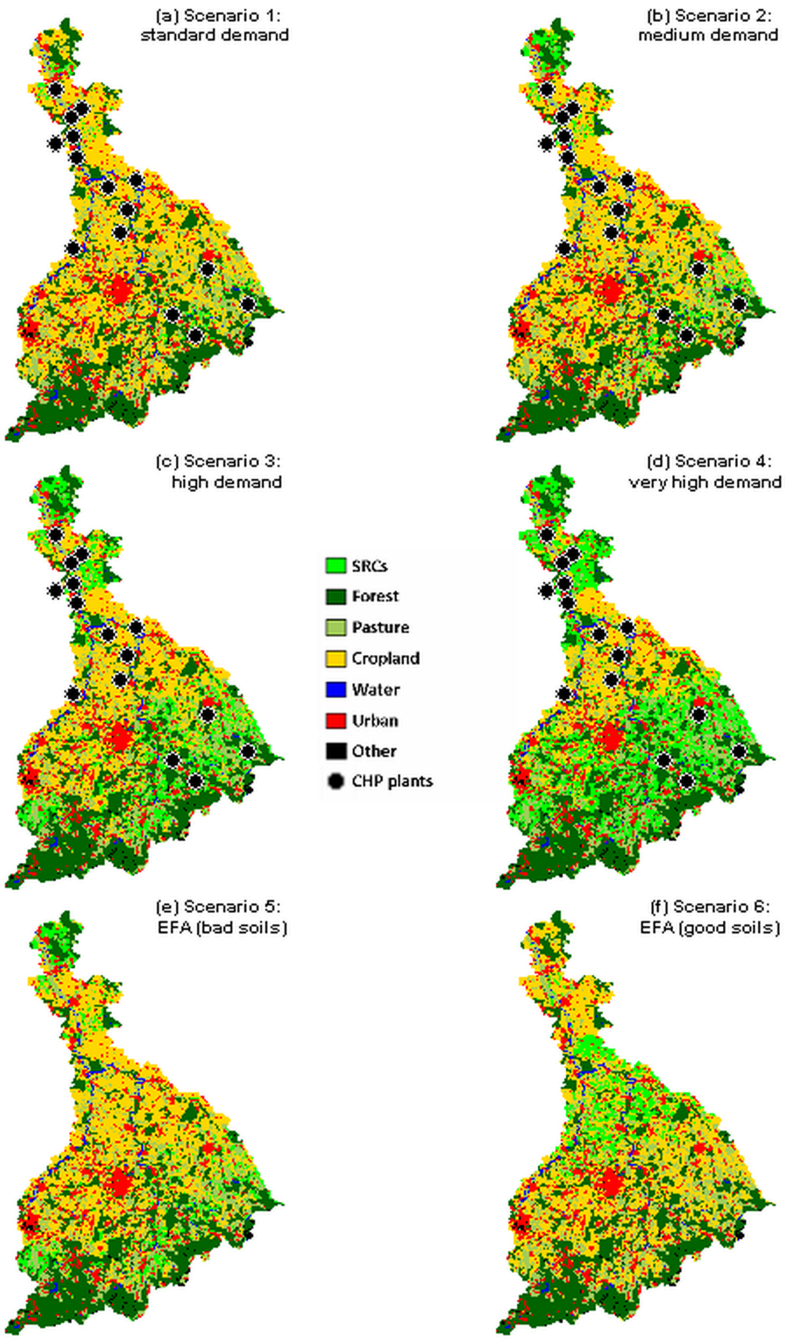


Figure 3.2: Deployment of SRCs in the Mulde watershed for four economic (1–4) and two policy-driven (5–6) scenarios. The economic scenarios are based on the economic simulation model. The policy scenarios reflect the potential deployment of SRCs to fulfill the requirements for EFAs (ecological focus areas). The dots indicate existing CHP plants (Das et al., 2012).

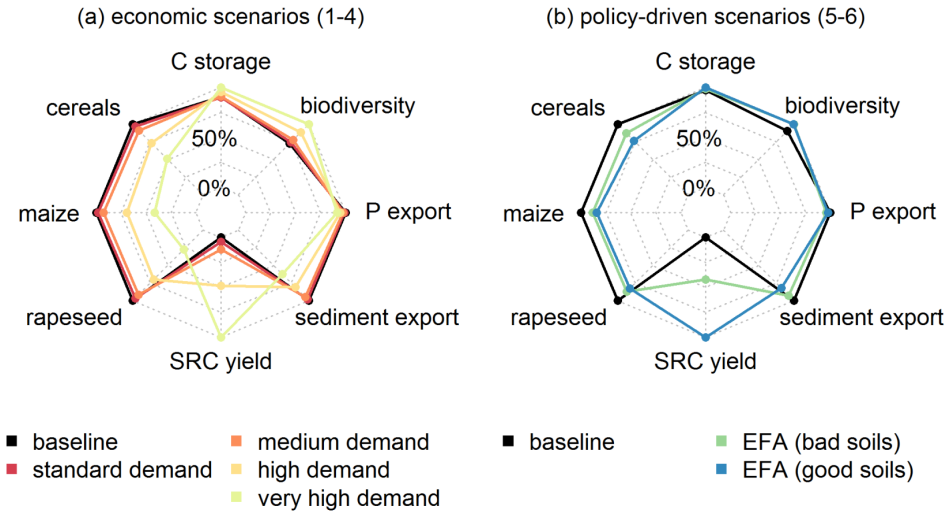


Figure 3.3: Trade-offs between provisioning and regulating ESS in (a) the economic and (b) the policy-driven scenarios, each set compared to the baseline scenario (black line). For each ESS, the scenario values are normalized with respect to the maximum value obtained; in other words, the maximum value of all scenarios is set to 100% and differences of the remaining scenarios are given in percent of the maximum value. For most of the ESS, higher values imply a better performance; a lower value is only better for P and sediment export.

regulating ESS and biodiversity. For example, in scenario 3, compared to the baseline scenario, SRC deployment on 14% of the study area synergistically increased biodiversity (+22%) and carbon storage (+5%) and reduced P (-5%) and sediment export (-19%) from a regional perspective.

Interestingly, the two policy-driven scenarios led to different trade-offs. SRCs placed on good soils positively affected SRC yield (403 000 t per year), carbon storage (+3%) and sediment export (-18%) at high costs of annual crops (ranging from -16% to -23% depending on the crop) (see scenario 6 in Table C.1 and C.2 in Appendix C). In contrast, SRCs placed on bad soils less positively affected SRC yield (170 000 t per year); annual crops were less negatively affected (ranging from -12% to -13% depending on the crop). It also led to a slightly higher reduction in P export (+4%) and a less positive effect on sediment export (-7%) and carbon storage (+1%) (see scenario 5 in Table C.1 and C.2 in Appendix C). Effects on biodiversity hardly differed between the two policy-driven scenarios (ranging from 10% to 11%).

3.5 SRC IMPACTS ON REGULATING ESS BUNDLES

Most of the ESS bundles, i.e., locations with a set of comparable ESS values, prevailed independent of the share of SRCs in the landscape, which varied between the scenarios (see Figure 3.4a). Only ESS bundle 2 strongly differed between the base-

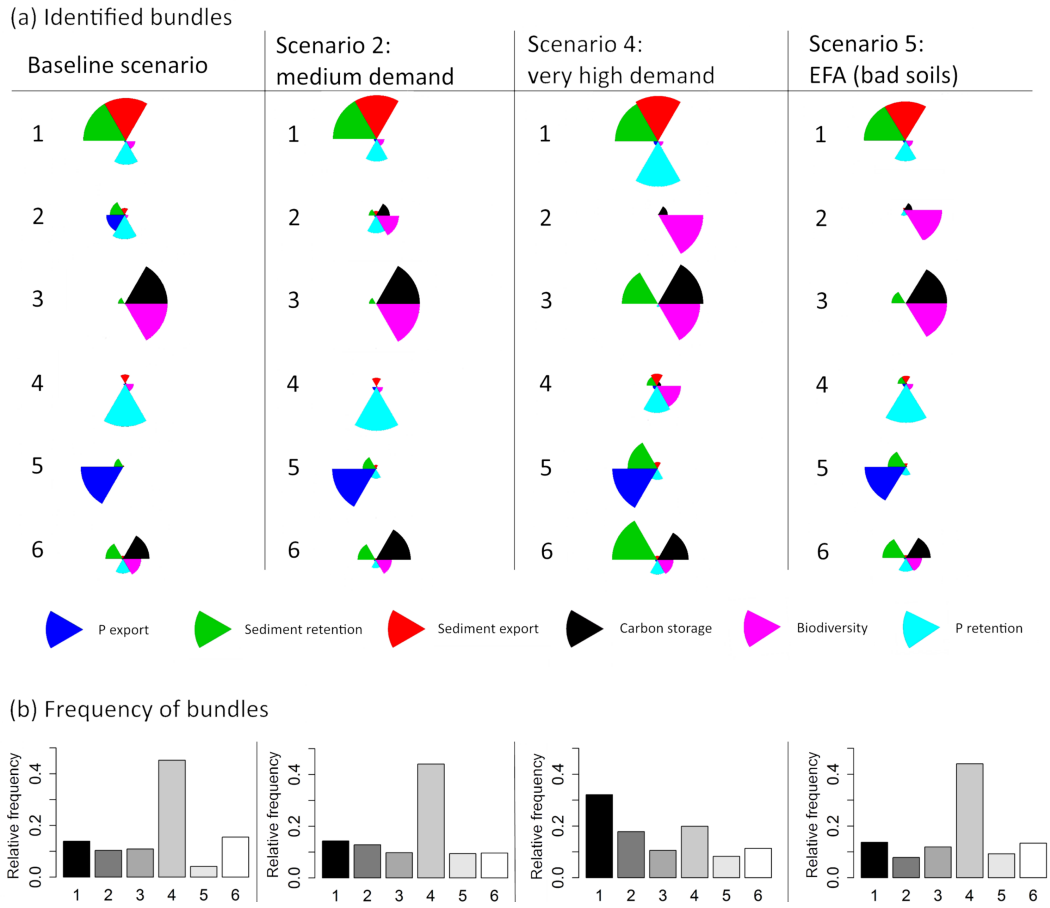
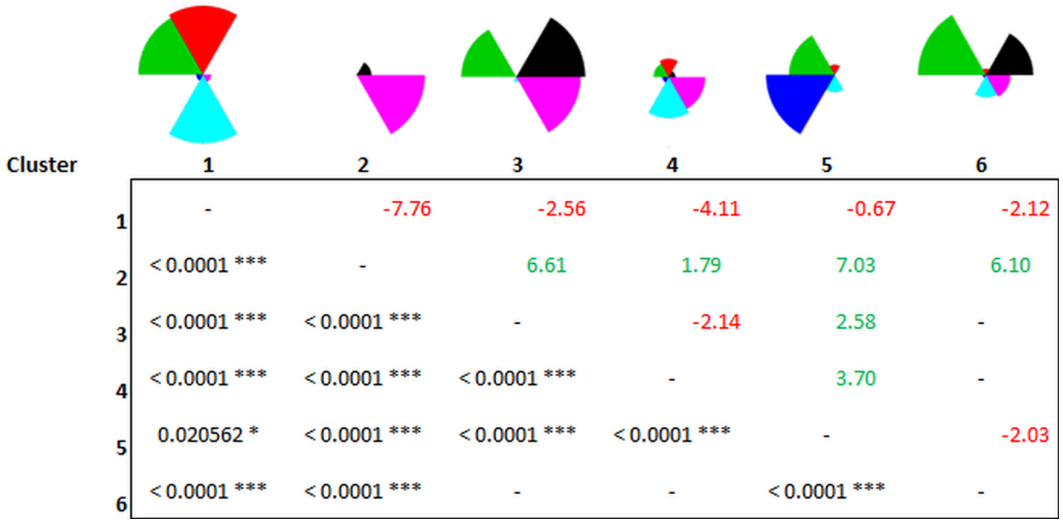


Figure 3.4: Identified ESS bundles (a) and their frequency (b) for the baseline scenario, two economic scenarios and a policy scenario. The highest arithmetic mean value for each ESS category is used as the maximum to scale the radar charts. The frequency of the ESS bundles is based on K means.

line scenario, scenario 2 (medium demand) (balanced low-value bundle) vs. the more homogeneous scenarios 4 (very high demand) and 5 (EFA (bad soils)) (high biodiversity bundle). Also bundle 4 in scenario 4 (biodiversity and P retention) slightly differed from the other scenarios.

However, the frequency of the respective ESS bundles changed more strongly (Figure 3.4b). For example, bundle 2 with a high biodiversity value was much more frequent in scenario 4 than in scenario 5. Also bundle 1 (sediment and P retention and sediment export) was more frequent in scenario 4, but bundle 4 (P retention and biodiversity) was less frequent than in the other scenarios. This might be due to the fact that increased SRCs seemed to enhance the frequency of bundle 1 (sediment and P retention and sediment export). Especially P and sediment retention became more frequent in the economic scenario 4 (bundle 1) compared with the other scenarios; this partly reflects the dominance of SRCs in scenario 4 retaining



Cluster	1	2	3	4	5	6
1	-	-7.76	-2.56	-4.11	-0.67	-2.12
2	< 0.0001 ***	-	6.61	1.79	7.03	6.10
3	< 0.0001 ***	< 0.0001 ***	-	-2.14	2.58	-
4	< 0.0001 ***	< 0.0001 ***	< 0.0001 ***	-	3.70	-
5	0.020562 *	< 0.0001 ***	< 0.0001 ***	< 0.0001 ***	-	-2.03
6	< 0.0001 ***	< 0.0001 ***	-	-	< 0.0001 ***	-

Figure 3.5: Percentage of SRC characterizing ESS bundles in scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to the cluster with the lower ordinal number; a negative value for the standardized β indicates that an explanatory variable is contributing to the cluster with the higher ordinal number. The entire regression results are listed in Appendix D.

more P and sediment from agriculture. The share of SRCs in the landscape made the beneficial balanced bundle 6 (sediment and P retention, carbon storage, and biodiversity) less frequent compared with the baseline scenario.

We applied a binomial logistic regression model to analyze the site-specific factors that determine the occurrence of different bundles in scenario 4 and to determine the role of SRCs relative to other factors. A higher share of SRCs surrounding a site enhanced the occurrence of bundles 2 and 4, see Figure 3.5. In that respect, a higher share of SRCs enhanced either (i) biodiversity or (ii) biodiversity, and P retention. A higher share of SRC weakened the occurrence of bundle 1 (sediment export and retention and P retention). However, the share of SRCs surrounding a site had little effect on the occurrence of the balanced bundle 6. In contrast, a higher slope and a higher available water holding capacity distinguished the balanced bundle 6 from the unbalanced bundle 5 with a dominance of P export (Table 3.3). Vice versa, a higher precipitation characterized bundle 5. The high explanatory power of the biophysical factors for the balanced ESS bundles and the rather low explanatory power of the share of SRCs showed that modifying landscape composition might be insufficient as exclusive measure (e.g., a high share of SRCs in the landscape to fulfill EFAs).

Table 3.3: Factors characterizing ESS cluster 5 and 6 for scenario 4 (backward logistic regression; p<0.001 (***), p<0.01 (**), p<0.05 (*), p<0.1(.)). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 5; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 6. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1317.1, df = 13, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2 = 30.7, df = 3, p = 9.8e-7).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	14.1910	0.8487	16.7200	<0.0001	***
Topography and soil parameters					
Elevation [m]	-7.8992	0.7950	-9.9360	<0.0001	***
Slope [%]	-12.1899	0.6934	-17.5800	<0.0001	***
Aspect [°]	0.6754	0.3015	2.2400	0.0251	*
Curvature [score]	-4.9453	0.7270	-6.802	<0.0001	***
Effective rooting depth [mm]	-2.5250	0.5256	-4.8040	<0.0001	***
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	-1.2373	0.5778	-2.1410	0.0322	*
Available water holding capacity [cm cm^{-1}]	-10.7915	1.5974	-6.7560	<0.0001	***
Climate					
Precipitation [mm]	4.4494	0.5605	7.9380	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	-4.5254	0.5381	-8.4100	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	-3.9183	0.5590	-7.0090	<0.0001	***
SRC, 5 km buffer [%]	-2.0335	0.3939	-5.162	<0.0001	***
Urban, 5 km buffer [%]	0.8486	0.4872	1.7420	0.0815	.
Water, 5 km buffer [%]	-2.6205	0.4617	-5.6760	<0.0001	***

3.6 DISCUSSION

3.6.1 *Ecosystem services and biodiversity under economic and policy-driven scenarios*

A major aim of this study was to analyze the impact of SRCs on ESS and biodiversity and to identify synergies and trade-offs under different economic and policy-driven scenarios. By investigating different scenarios, we assessed a range of possible futures and thereby the maximum variation in outcomes; with the actual outcome being bounded by this range. SRCs are discussed as sustainable 2G feedstock for energy production. Our approach of placing SRCs in the landscape by modeling farmers' decisions contributes to filling the gap in existing research which synthesizes mostly plot/field scale studies for ESS (Milner et al., 2015) and conceptually discusses but does not test the beneficial impact of SRCs on ESS at the regional scale (Manning et al., 2015). Only few studies such as Fürst et al. (2013) have assessed the impact of SRCs on multiple ESS and biodiversity at the regional scale, but without modeling farmers' decision-making to assess commercial SRC deployment. Simulating farmers' decisions and indirect market interactions allowed us to develop spatially explicit SRC distributions at a commercial scale, given the assumptions made in the economic simulation model. This enables an environmental and ESS impact assessment as requested by several authors for 2G feedstocks, e.g., Holland et al. (2015). We spatially explicitly model SRC allocations and impacts on multiple ESS, while existing SRC impact assessments, e.g., Milner et al. (2015), focus on carbon storage.

In the investigated economic scenarios, farmers preferably cultivated SRC plantations in the southern and northern part of the Mulde watershed where sites with low-quality soils dominate. SRCs seem to compete with annual crops on these low quality soils. In that respect, we can confirm Hellmann and Verburg (2011, p. 2414) who assume "[...] that it is unattractive to cultivate biofuel crops on locations with relatively very high yields of cereals and root crops due to economic competition". Furthermore, our model results indicate that SRCs are established in the proximity of existing CHP plants. This is in line with Kocoloski et al. (2011) and Vanloocke et al. (2010) who state that 2G feedstocks are likely to be clustered around biorefineries. In scenario 1 (standard demand), we tested the impact of switching the current input of CHP plants in the Mulde watershed to wood chips from SRCs. We showed that the investigated provisioning and regulating ESS and biodiversity would be only slightly affected in scenario 1. In particular, food production will not be affected much. Only substantial promotion of SRCs would increase biodiversity and carbon sequestration as well as reduce sediment and P export. This is in line with Fürst et al. (2013) who showed for a case study in Central Saxony, Germany, that a substantial increase of SRC production by up to 30% (depending on the region) would beneficially affect the provision of ESS and biodiversity. Meehan et al. (2013) also showed a decrease in P export to surface water and an increase in carbon sequestration by switching from annual crops to perennial grasses. For the ESS

assessment, we chose InVEST and GLOBIO as they allow us to model multiple regulating ESS with a high reliability relative to the effort involved, e.g., Meyer et al. (2015). Given that we conduct a relative comparison of the different scenarios, the possible inclusion of slight imprecisions, which are present to an equal extent in all scenarios, pose no major disadvantage.

Besides the economic scenarios, we assessed instruments in two policy scenarios for their impact on SRC deployment and ESS. We compared the more likely policy scenario 5 (EFA (bad soils)) with the rather hypothetical scenario 6 (EFA (good soils)). Both scenarios showed different impacts on the regarded ESS. In scenario 6, SRC yield, carbon storage, and sediment export are more positively affected at high costs of annual agricultural production. In contrast, scenario 5 is slightly more beneficial for P export while crop production is not tremendously decreased. Both scenarios have the same share of SRCs in the landscape, but with differing spatial distribution answering the research need raised by Holland et al. (2015). They ask whether the distribution of feedstocks might affect the provision of ESS. This underlines the importance of aiming at more realistic distributions of potential energy crop deployment (e.g., for example by explicitly modeling farmers' decisions). In addition, it shows the potential to reflect on the current EU policy of coupling subsidy payments to the provision of EFAs. Our study reveals that the rules regarding the EFAs' properties need to be specified depending on the environmental goal. For example, the same share of SRCs in the landscape led to significantly different reductions of sediment export compared to the baseline scenario (i.e., 7% (scenario 5) or 18% (scenario 6); see Table C.1 in Appendix C). Therefore, the CAP should include the quality of the options available to fulfill EFAs as well as the biophysical site conditions. In addition to the share of SRCs in the landscape, biophysical factors were also important for increasing the frequency of balanced ESS bundles, see Table 3.3 and Tables D.2 to D.15 in the Appendix D. Therefore, a policy combining beneficial biophysical factors and land use types might more strongly enhance ESS supply.

We clustered ESS bundles to analyze how the share of SRCs in the landscape affected the occurrence and frequency of the respective bundles. Thereby, we assessed occurring trade-offs between multiple ESS as well as biodiversity at the regional scale, which are inherent in the 2G feedstock expansion (Power, 2010; Raudsepp-Hearne et al., 2010; Werling et al., 2014). In that respect, our approach helps to balance competing services for deployment decisions as required by Holland et al. (2015). Comparing all scenarios with the baseline scenario, the different shares of SRCs did not enhance the balanced bundle 6. Comparing the different bundles in scenario 4 with a binomial logistic regression model, we showed that SRCs especially enhanced either (i) biodiversity (bundle 2) or (ii) biodiversity, and P retention (bundle 4), but did not enhance the balanced bundle 6. Such analysis on ESS bundles broadened the findings for single ESS from the synthesis by Holland et al. (2015). Balanced ESS bundles are unlikely to be obtained even with a high share of SRCs in the landscape. Their occurrence can be better explained by biophysical

factors. Overall, the beneficial impact of SRCs on multiple ESS and biodiversity as discussed in several studies (e.g., Manning et al., 2015; Holland et al., 2015) was found to be rather low for the individual SRC plot and the regional scale.

3.6.2 *Methodological reflections and transferability of methods and results*

In this study, we used a spatially explicit economic simulation model to simulate farmers' decisions on their agricultural activity. While the farmers decide according to their individual conditions (yield and transport costs), endogenous markets mediate interactions among them. Agents react to market signals and in turn influence the market price which is given by the balance of demand and supply. Therefore, our approach builds on equilibrium theory as demand and supply meet in the equilibrium in the course of time. With the depiction of human decision-making depending on individual, heterogeneous cultivation conditions and the indirect market interaction, the presented modeling approach is close to the agent-based modeling (ABM) framework (Holland, 1992). However, prominent ABM characteristics such as direct interactions between agents and heterogeneous agents' decision-making are currently not incorporated into the model, so that it resembles a cellular automaton approach in some aspects.

The economic simulation model was developed to evaluate potential futures of SRC deployment when this production practice will reach its mature commercial phase. In this model, we assumed profit maximization as decision rule. Although this rational and self-interested decision-maker is widely accepted in economics, non-commercial factors are also believed to influence agricultural decisions (Renting et al., 2009). In Germany, farmers' interested in SRC practice are provided with advisory material (e.g., the manual of Skodawessely et al. (2010)) or profitability calculators provided by projects (e.g., AGROWOOD, 2015). Therefore, we implemented the profit maximization as determining decision criterion suggested there. We assumed farmers' decision-making to be homogeneous because the structure of farms in the study region is very homogeneous. Large cooperatives organized as legal entities succeeded the state-owned farms that existed during the GDR period and account for about three quarters of the entire agricultural area in eastern Germany (Blumöhr et al., 2011). In economic models, often budget constraints are incorporated to reflect limitations individuals face due to their available income. In this study, we did not include budget constraints as land rather than money is the critical input factor. The overall soil quality in the study region is rather high; therefore, farmers expectedly always cultivate their land if not hindered through policy (e.g., EFAs are mandatory as implemented in scenario 5 and 6) or other measures. Here, the question is rather, which demand level makes SRCs more profitable than annual crops. Therefore, the budget constraint is negligible.

Beyond modeling SRC deployment in the commercial phase, one could also model the current process of SRC deployment (e.g., to explain the slow deployment of

SRCs). This would require additional factors such as practical challenges associated with SRCs and other new land use options, which could be influential (Glithero et al., 2013; Sattler and Nagel, 2010; Sherrington et al., 2008). In this context, social influence from neighbors or decision-making concepts such as early or late adopters (as for example done in Berger (2001)) should be incorporated. Future research could adapt the model to address pre-mature commercial phases by including social influence or different decision types, so that the model more closely resembles an ABM framework.

Considering the discussed assumptions, the economic simulation model can be applied to different regions and policy settings. Within the assumed profit maximization, we focused on the major site-specific influence factors of cropping decisions (i.e., soil quality and distance to CHP plants). From the environmental perspective, this is an appropriate assumption for our study area as the entire arable land is located in a plain area with moderate variation in slope and available water holding capacity. In study regions, which also fulfill these characteristics, the economic simulation model can be reapplied to simulate SRC deployment if spatial data on soil quality or CHP plants' distribution is available. If further biophysical factors, such as slope, are heterogeneous within the study region, these could be included in the economic simulation model.

However, without reapplying the ABM, the results of the ESS assessment should already be representative for similar German soil climate clusters ("Boden-Klima-Räume"), which comprise large areas of eastern Germany (Saxony and Thuringia (Saxon-Thuringian Hills and Upper Lusatia)) (Roßberg et al., 2007). In addition, this region is one of Germany's major crop production areas. With respect to land use intensity, agricultural companies and field structures in this region remained mostly stable after the re-privatization of the Agricultural Production Cooperatives (Blumöhr et al., 2011), which allow for comparable highly mechanized land management. Further environmental transfer of the results beyond Germany might be equally feasible with different approaches that control for environmental heterogeneity as developed in Meyer et al. (2016).

From a policy perspective, increasing demand in the economic simulation model can resemble instruments like the promotional policies under the Renewable Energies Act in Germany and other national laws implementing the EU RED that affect the prices for woody biomass. Furthermore, these market-related changes may also be affected by emerging novel conversion technologies (Edel and Thrän, 2012). Beyond the EU RED, other environmental policies such as forest protection policies and reforestation initiatives may also affect biomass demand and cause regional shifts (Meyfroidt et al., 2013). In that respect, our approach of coupling an economic model with ESS and environmental assessments may also be applied to assess the impact of changing supply and demand patterns in the forestry sector on regional ESS.

All assumptions discussed above influence our model results. In our study, however, the aim is not to predict land use in the Mulde watershed, but rather to derive

some general insights and mechanistic understanding. Therefore, we follow a scenario approach. Scenarios hardly predict the exact land use that will occur, but rather show the range of potential futures (see for example Amer et al. (2013)), i.e., in this study SRC deployment in the Mulde watershed. Thereby, we assess the maximum range of possible outcomes and expect that the actual outcome will lie within this range. Extensive empirical model validation on current SRC deployment is impossible; SRCs are seldom deployed which impedes an empirical validation of simulated land use patterns with actual land use patterns.

Coupling an economic simulation model with environmental assessment tools such as InVEST and GLOBIO offers several advantages over simpler suitability assessments (e.g., Meehan et al. (2013) or Tölle et al. (2014)). The latter often rely on predefined thresholds, but miss farmers' decision-making in the site selection process. In our approach, modeling farmers' decision-making determines the spatial deployment of SRCs. This makes it possible to apply the same methodology to different settings (e.g., other decision processes or different economic or policy scenarios) and to investigate how this changes the allocation of SRCs without predefined suitability rules. Suitability rules are unlikely to be transferable even at the national scale due to heterogeneous management and environmental conditions.

3.7 CONCLUSION

In this study, we assessed how SRCs would affect multiple ESS and biodiversity under different economic and policy-driven scenarios in the Mulde watershed in Central Germany. We found that only a substantial increase in SRC production areas will considerably reduce food production and increase the provision of regulating services. However, there is hardly any increase in the number of sites with balanced ESS supply due to larger shares of SRCs in the landscape:SRCs do not significantly enhance the multifunctionality of the landscape. By modeling land use decisions, we simulate a more realistic spatial distribution of bioenergy feedstocks under future scenarios. Our approach can be extended to other novel land use options other than bioenergy. Coupling spatially explicit economic simulation models with environmental and ESS assessment models, we can contribute to a comprehensive impact assessment of novel and hardly deployed land use options in terms of their effects on multiple ESS.

Part II

SUPPLEMENTARY FEEDING PROGRAMS IN PASTORAL SYSTEMS

4

GOVERNMENTAL RESPONSE TO CLIMATE RISK: MODEL-BASED ASSESSMENT OF LIVESTOCK SUPPLEMENTATION IN DRYLANDS

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4.1 ABSTRACT

Drylands cover 40% of the world's surface and provide the basis for the livelihoods of at least one billion people. Pastoralists in these regions face risk and uncertainty due to highly variable climatic conditions. Therefore, and due to global change, novel risk-coping management strategies have evolved in recent decades. For example, in many pastoral regions in drylands government supplementary feeding programs are commonly introduced as a strategy to address multiple societal challenges related to climate risks, such as poverty alleviation or the maintenance of resilient pastures, in a cost-efficient way. Therefore, it is crucial to assess government supplementation programs from a multi-criteria cost-benefit perspective. Using a generic, ecological–economic simulation model we analyze the potential benefits and threats of supplementary feeding in the form of government subsidies. Our results show that currently practiced supplementary feeding strategies may cause damage in the long term because of unintended side-effects such as degradation and cost explosion. In addition, we present a novel risk-coping strategy that supports farmers and is also both ecologically and economically sustainable. Last but not least, it is shown that government supplementation programs are only cost-efficient if they are regionalized and adapted to the specific ecological characteristics of the rangeland utilization systems in question.

4.2 INTRODUCTION

Drylands cover 40% of the world's surface and provide the basis for the livelihoods of at least one billion people (UNCCD, 2010). Pastoral systems are of particular importance in these regions as precipitation is scarce and highly variable, making crop farming difficult. Pastoralism describes a household strategy system where more than 50% of the gross revenue depends on livestock activities (Baumann, 2009). It forms a significant part of the national economies in developing countries (Davies et al., 2010) such as in Morocco where it contributes 25% to the agricultural GDP (Davies et al., 2010).

Dryland climatic conditions pose different challenges for pastoralists. Apart from facing income risks due to highly variable precipitation and drought, they are also faced with the danger of rangeland degradation and the income loss associated with it, which are potentially triggered by scarce precipitation and over-utilization of the rangeland and its natural resources (Sissoko et al., 2011). The estimated income loss due to rangeland degradation is $42 billion per year (UNCCD, 2010). Management strategies to cope with these challenges are needed to alleviate poverty and secure pastoralists' livelihoods while sustaining the ecological integrity of the rangeland.

Globally, various strategies are being used to cope with climate-related income risks and poverty. One recent approach involves providing pastoralists with finan-

cial support through government programs. Multiple novel governmental risk coping options have evolved. One example is the introduction of grazing reserves which farmers can use in times of drought (FAO, 2010). This concept, based on the idea of mitigating degradation by regulating pasture access, is inspired by tradition, as these grazing reserves have existed already for a long time. Another strategy with a long history of use is destocking, which is based on the idea of managing the livestock to match fodder demand and supply. Under destocking programs, farmers are given incentives to sell livestock when natural fodder is scarce (FAO, 2010). In Kenya, for example, destocking programs were applied during the droughts in 1999 and 2000 (Aklilu and Wekesa, 2001). As a counterpart to these programs, restocking programs have been implemented to help farmers to recover their herd after a breakdown caused by drought. One example of this kind of policy is the $330 million Reconstruction and Rehabilitation Programme for Agriculture and Rural Areas formulated by the Government of Bosnia and Herzegovina (IFAD, 1997, 1999). Some governments also offer weather-based financial risk management instruments such as rain-index insurances (Müller et al., 2011) aimed at providing farmers with financial support in times of low precipitation. All of these government programs address multiple climate-related societal challenges such as poverty alleviation by enabling farmers to withstand times of crises, value addition and the maintenance of resilient pastures. Moreover, these goals have to be achieved in a cost-efficient way. But they also may cause unintended, unwanted side effects that ought to be mitigated. For example, Carpenter et al. (2009, p. 1306) name the "dysfunction of institutions and policy" as one reason for degrading ecosystem services. To address these challenges, a comprehensive understanding of the long-term impacts of these programs on the social-ecological functioning and performance of pastoral systems is required.

This study focuses on a government risk-coping strategy of increasing global relevance: subsidized supplementary feeding in times of natural fodder shortage. Policymakers and development agencies have recently begun to include supplementation of livestock in their emergency programs, for instance in North Africa and West Asia (Hazell, 2000, p. 93), or as part of development projects (cf. the Project of Pastoral Development and Livestock in the Oriental PDPEO in Morocco, Mahdi (2007)). Under such programs, farmers receive supplementary fodder in order to maintain their livestock as the source of their livelihood. In Morocco, this approach showed some success: a drought in 1995 resulted in a cereal production decline of 17% of the preceding year, while livestock numbers were not much affected (Hazell et al., 2003). However, despite the positive effects of this form of drought relief, negative impacts may also result. Enabling the maintenance of high livestock numbers during droughts leads to increased grazing pressure which, in turn, is accompanied by an increasing risk of degradation. For example, in New Mexico, supplementary feeding resulted in 15–25% higher stocking rates than if the subsidies were not available to farmers (Hess and Holechek, 1995). This could lead to degradation in the long term, which would make the strategy ecologically unsustainable. This highlights

the urgent need to reveal the factors determining the potential benefits and threats of supplementary feeding strategies. Müller et al. (2011) showed that an appropriate (rather low) frequency of payments reduces negative side effects of rain-index insurances. We therefore hypothesize that the potential benefits and threats of a supplementation program are influenced by its specific design. In this study, we investigate the role of the way supplements are used (i.e., to avoid destocking or to rest the pasture) as well as the role of timing, intensity and frequency of supplementation. As cost-efficiency of the supplementation programs is of particular relevance for the government, tracking the costs as well as the benefits is crucial. For example, a drought in Tunisia 1988/89 resulted in coping costs of $82 million and of $30 million in Morocco in 1992 (Hazell, 2000). In our study, two different economic perspectives of assessment are incorporated - the perspective of the farmer (i.e., long-term income as well as income risk) as well as that of the government (i.e., net economic benefit of subsidy programs).

Several subsidy programs are based on traceable measures. For instance, under the already addressed rain-index insurances, farmers receive pre-specified payments when the current precipitation falls below a pre-specified threshold (Skees and Barnett, 1999). Such programs are advantageous due to their transparency and their simplicity with regard to monitoring (Miranda and Vedenov, 2001; Skees and Barnett, 1999). In a similar manner as rain-index insurances, the subsidy for supplementary fodder can be linked to a precipitation index. Therefore, in this study, we incorporate supplementary feeding strategies that are granted based on current precipitation levels and compare them to a strategy under which supplements are granted in times of need, irrespective of current precipitation.

The study also examines the extent to which the performance of a supplementation program is influenced by regional context, especially the biophysical conditions of the pastures and the ecological characteristics of the vegetation. Of particular interest here is the capability to build up biomass reserves as a key mechanism for regeneration (buffer capacity), or population-dynamic characteristics of the livestock such as fecundity.

The main aim of this paper is to assess the cost-efficiency performance of government supplementary feeding programs in meeting multiple societal challenges: poverty alleviation, value addition and maintenance of resilient pasture. By using an ecological–economic simulation model and applying a cost-benefit approach, we evaluate two currently practiced and one newly designed supplementary feeding strategy from a multi-criteria perspective. The two currently practiced strategies are characterized by supplements granted in years of forage shortage and in drought years, respectively. Under these strategies supplementary feed is used to avoid destocking. The newly designed strategy supplements in droughts to avoid destocking and additionally in the year directly after a drought to rest the pasture. We analyze how potential benefits and threats of supplementation depend on both the specific design of the supplementation strategies and the characteristics of the regional context.

4.3 METHODS

4.3.1 *The model*

Our model is a modified version of the generic, economic-ecological simulation model described in Müller et al. (2015). Here, we present a short description of the model. The full model description using the ODD (Overview, Design Concepts and Detail)-protocol (Grimm et al., 2006, 2010) can be found in Appendix E.

4.3.1.1 *Purpose and basic idea of the model*

The model was developed to analyze the ecological and economic implications of supplementation strategies in the form of subsidies provided by government agencies on a semi-arid rangeland system. The model is stylized and explicit in representing the main features of a semi-arid rangeland system, but is simple enough to demonstrate the consequences of different supplementation strategies (Schlüter et al., 2013).

For simplicity, we model one livestock-breeding household possessing one herd of sheep. The household depends exclusively on livestock production for its livelihood. It is assumed that no purchase of livestock takes place. Hence, herd growth is driven solely by birth processes. The interrelated processes between livestock and vegetation dynamics are simulated for a time horizon T of 60 years. The model runs in annual time steps.

The ecological model part of the stylized semi-arid rangeland corresponds to the ecological model described in Martin et al. (2014). As is common for semi-arid ecosystems (Linstädter and Baumann, 2013; Ruppert et al., 2012) the main driver of forage dynamics is annual precipitation r_t. The pasture is assumed to consist of an abstract perennial plant type (i.e., perennial grasses or shrubs), where all aboveground parts are accessible to smallstock. This perennial plant type is characterized by two functional parts: green G_t and reserve biomass R_t (Müller et al., 2007; Martin et al., 2014). The term green biomass refers to all photosynthetically active parts of aboveground biomass, which is assumed to constitute the main forage resource for livestock. Reserve biomass describes the non-photosynthetic reserve biomass (either below- or aboveground) which serves as storage (termed after Noy-Meir (1982)). Reserve biomass is influenced by rainfall and by grazing management history (O'Connor, 1991). Livestock is modeled as one herd of sheep characterized by its size S_t. The management strategy that is applied during the whole time span is characterized by when and for which purpose supplementary feeding for livestock is granted (e.g., for pasture regeneration or for maintenance of livestock).

4.3.1.2 *Process overview and scheduling*

Here, the processes of the model are briefly specified to give a general overview of the model and its dynamics. For a detailed description of each of the processes, see Appendix E. The processes are presented according to their sequence within one time step.

Process 1: Precipitation. The precipitation r_t for each year is randomly sampled from a log-normal distribution.

Process 2: Dynamics of green biomass. The green biomass G_t is determined by two variables: precipitation r_t and current reserve biomass R_t.

Process 3: Herd size adjustment. Animals are born at a constant birth rate b (with a standard value of 0.8 - for reference please see Appendix E). Here, population-dynamic characteristics of the livestock can be investigated by varying the birth rate b. Natural death and animal condition are not explicitly modeled because it is assumed that older animals and animals in poor condition are destocked first. Following birth, we calculate the number of animals that need to be sold D_t because of lack of forage on the pasture. For this purpose, we assume that the farmer adapts his herd to the available forage always keeping as many animals as possible. In doing so, we follow insights from studies on pastoral systems in Africa that showed that keeping large herds is used as an insurance against environmental shocks (Lybbert et al., 2004; Robinson and Berkes, 2010). Further decision constraints such as social norms also play a role in pastoral systems. These norms may mitigate negative impacts (for example the overuse of common natural resources introduced as the "tragedy of the commons" by Hardin (1968)). In this study, we focus on one pastoralist and therefore do not consider these mechanisms. In process 3, we calculate the livestock numbers without possible supplementation and readjust in process 4, depending on the specific supplementation strategy.

Process 4: Supplementary feeding. Supplementation is regarded as a subsidy given by the government, as is practiced in many pastoral systems in drylands. The strategies differ in terms of the type of supplementation (whether grants are used to avoid destocking or to relieve pastures) and in the timing (precipitation-dependent or not). The four main strategies under investigation here are:

1. No supplementation ("No feeding"; short "No")
2. Supplementary feeding when natural forage is not sufficient ("Feeding when needed"; short "FWN")
3. Supplementary feeding in a drought to avoid destocking ("Feeding in drought"; short "FID")
4. Supplementary feeding in a drought to avoid destocking and after supplementation to relieve pasture ("Feeding in drought and post-drought"; short "FIDPD")

A drought occurs when current precipitation r_t falls below a previously fixed threshold. For each of the main strategies this threshold (r_{thr}) and the maximal amount of supplements (mf) are set at the beginning of a simulation, and represent the grantor's willingness to grant supplements (how often and how much). The number of animals being supplemented $S_{suppl,t}$ (either to avoid decreasing herd size or to rest the pasture) is determined based on the supplementation strategy and current precipitation. Livestock numbers S_t and vegetation G_t are adjusted accordingly.
Process 5: Dynamics of reserve biomass. At the end of a timestep the reserve biomass R_t is adjusted depending on the portion of the pasture grazed and by taking natural decay into account. In doing so, the biophysical characteristics of the vegetation, namely its capability to build up reserves as a key mechanism for regeneration (buffer capacity), can be varied in the model by the recovery rate of reserve biomass based on green biomass w (with a standard value of 0.8 - for reference please see Appendix E).

4.3.2 *Evaluation techniques*

4.3.2.1 *Assessment criteria*

The aim of this study is to investigate the long-term effects of different supplementation strategies in terms of their economic and ecological sustainability. To do so, we evaluate these strategies over a time horizon of 60 years.

The annual reserve biomass R_t is used to classify the ecological condition of the pasture. This is a more appropriate measure of pasture condition than the green biomass G_t. The latter strongly depends on the current rainfall r_t and the herd size of the livestock, while the former is a good measure of the history of the dynamics and hence of the long-term influence of rainfall and grazing on the biomass.

From an economic point of view, two different perspectives are incorporated - the perspective of the farmer and that of the government. Firstly, we evaluate the supplementary feeding strategies based on the induced economic situation of the farmer. To do so, we take herd size as a measure of the economic capital of the farmer to reflect the importance of herd accumulation as risk-coping strategy (Naess and Bardsen, 2013). We calculate the mean annual income $S_{mean,t}$ and the income variability $S_{CV,t}$ over the years to account for the income risk.

Note, however, that the supplementation strategies are implemented as subsidies and so paid by the government in this study. Thus, the respective costs are exclusively assigned to the societal, but not to the household scale. Therefore, besides the annual herd size S_t we observe the number of supplemented animals $S_{suppl,t}$ as a proxy for the costs incurred by the supplementary feeding strategies on the side of the grantor. To evaluate the economic balance between the household's benefit and the costs of the supplements, we calculate the farmer's herd size minus the costs of granted supplements in each year (from now on called "net economic benefit"). By integrating costs and benefits of the different groups affected by the program

under study, we follow the social cost-benefit analysis approach (see Cellini and Kee (2010)). Social costs-benefit analyses incorporate costs and benefits that "accrue to everyone in society" (Cellini and Kee, 2010, p. 494). We will refer to this measure by "net economic benefit" because no further benefits (e.g., ecological integrity of pasture) are incorporated besides the herd size as proxy of the farmer's income.

4.3.2.2 *Considered strategy space for optimization*

As elaborated in the previous section, the comparison focused on four main supplementary feeding strategies, each characterized by two parameters (mf [sheep] and r_{thr} [mm]). In the search for the optimal strategy presented in Section 4.4.3, we opened the strategy space by comparing a set of supplementary feeding strategies consisting of the four main strategies each with different strategy parameter combinations (three different amounts of supplements and three different rain thresholds below which supplements were granted). In total, 21 strategies plus the reference strategy with no supplementation were compared. For finding the optimal strategy in Section 4.4.3, the mean annual net benefit (as economic measure) and the coefficient of variation in livestock numbers across the years (as measure for the pastoralist's income risk) over a time horizon of 60 years were taken into account.

4.4 RESULTS

4.4.1 *Comparison of supplementary feeding strategies*

For a better understanding of the model behavior, the impact of the four supplementation strategies on ecological and economic state variables for one specific precipitation scenario is depicted in Figure 4.1.

In total, the supplementation strategies result in similar or even higher herd sizes compared to the case without supplementation. Thereby, herd sizes do not increase over the course of time as supplementation is only used to avoid destocking and not to enlarge the herd. Consequently, after a transient phase of about 20 years, the herd size stabilizes under all regarded strategies. In early years, the strategy "Feeding when needed" leads to the highest herd size. However, the same strategy leads to the strongest decrease in reserve biomass. In contrast, the novel supplementation strategy "Feeding in drought and post-drought", which combines feeding in drought to avoid destocking and after drought to relieve the pasture, leads to a comparably good pasture state and consequently also supports, in the long run, high sheep numbers compared to "No feeding" and "Feeding in drought". Hence, "Feeding in drought and post-drought" is competitive with "Feeding when needed" in terms of herd size in later years. On closer investigation of herd size dynamics, we see that the three supplementation strategies mitigate the risk of herd loss due to drought (for example in the years 11, 21 or 40 of the regarded rainfall parameter). In these

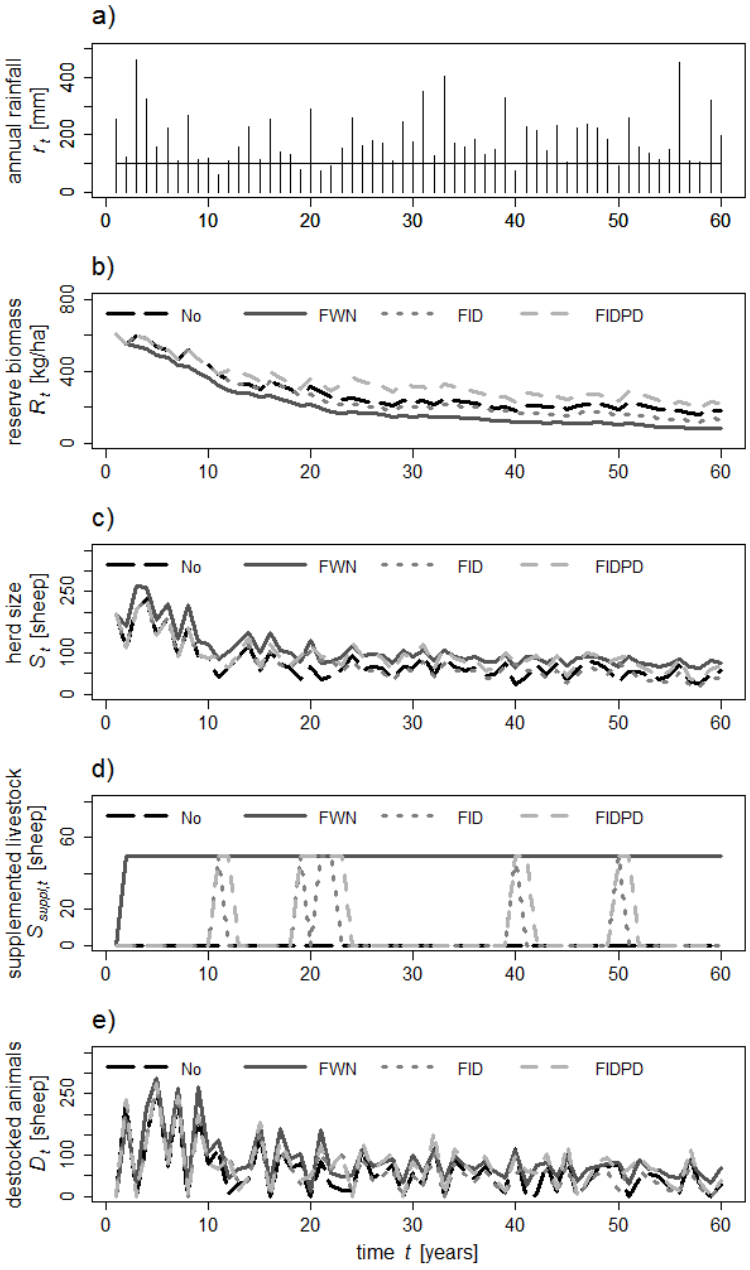

Figure 4.1: Ecological and economic state variables for the four supplementation strategies for a specific rainfall scenario. The black line in (a) indicates the rain threshold (r_{thr} = 100 mm) below which supplements are granted. The birth rate b is set to 0.8 and the recovery rate of reserve biomass w to 0.8. Explanation of abbreviations: "No": without supplementation; "FWN": supplementary feeding when natural forage is not sufficient; "FID": supplementary feeding in drought to avoid destocking; "FIDPD": supplementary feeding in drought to avoid destocking and after supplementation to relieve pasture.

years, the case without supplementation ("No") leads to a stronger decrease in herd size.

The number of animals that need to be destocked due to forage shortage is shown in Figure 4.1e. This measure can be seen as an additional proxy for the pastoralist's income besides herd size. The dynamics over time are similar to the herd size dynamics: at the beginning of the time horizon "Feeding when needed" leads to the highest herd sizes and destock numbers. However, after about 20 years "Feeding in drought and post-drought" is competitive in terms of destocked animals due to the reasons described above.

These results are based only on one specific precipitation scenario. To generalize, we performed further analyses over an ensemble of 500 different precipitation timelines. We will discuss the further effects of the different supplementation strategies based on means over the ensemble.

4.4.2 *Role of the design of supplementary feeding strategies*

In this section, we analyze how the frequency (r_{thr}) and the maximum amount (mf) of supplements, i.e., how often and how much the government is willing to grant supplementary feed, affect herd size $S_{mean,t=60}$ and reserve biomass $R_{mean,t=60}$ in year 60.

Figure 4.2 indicates that increasing supplementation mf can have different implications for herd size $S_{mean,t=60}$ and reserve biomass $R_{mean,t=60}$, depending on the supplementary feeding strategy implemented. Under the strategy "Feeding when needed", $S_{mean,t=60}$ and $R_{mean,t=60}$ respond oppositely (Figure 4.2a), under "Feeding in drought", both are declining (Figure 4.2b), while under "Feeding in drought and post-drought", both are increasing (Figure 4.2c). In case of "Feeding when needed", supplementation is provided in each year of fodder shortage, regardless of precipitation. This results in a generally enlarged herd size with increasing supplementation amount mf that increases the grazing pressure on the pasture and so decreases the reserve biomass in the long term. This indicates that, whenever the timing of the supplementation is decoupled from the precipitation, the herd size becomes decoupled from the biomass supply of the pasture leading to degradation. This makes the pastoral livelihood dependent on supplementation. In contrast to this, under "Feeding in drought", supplementation is provided in dry years only. Here, the livestock is prevented from destocking in these critical years. The preserved herd size, however, causes a problem in the following year where the pasture is not yet recovered and cannot withstand the grazing pressure anymore. The decreased reserve biomass limits the herd size in the long term, as no supplementation is provided in these normal years. A completely different picture emerges in case of "Feeding in drought and post-drought" where supplementation is provided both in dry years and the year after. Through this regime, supplementation prevents livestock destocking in dry years, but also reduces the grazing pressure and gives the pasture

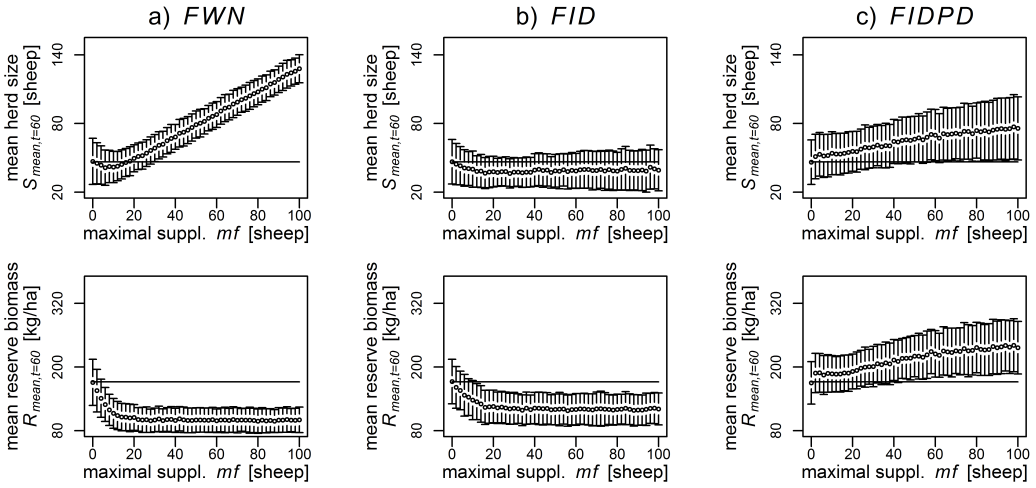

Figure 4.2: Comparison of the different supplementary feeding strategies by the mean herd size $S_{mean,t=60}$ (top row) and mean reserve biomass $R_{mean,t=60}$ (bottom row) in year 60 over 500 simulations for a variation of the amount of maximal available supplementary fodder (mf). The parameter rain threshold r_{thr} is set to 100 mm, the birth rate b to 0.8 and the recovery rate of reserve biomass w to 0.8. The horizontal line indicates the result when no supplementation is granted. Error bars indicate the standard deviation over runs of the according variable. Explanation of abbreviations: "FWN": supplementary feeding when natural forage is not sufficient; "FID": supplementary feeding in drought to avoid destocking; "FIDPD": supplementary feeding in drought to avoid destocking and after supplementation to relieve pasture.

time to recover in the following year. As a result, degradation is avoided and the pasture maintains its ability to nourish the livestock in a natural way. The higher the amount of supplementation mf is, the stronger the synergistic effect for $S_{mean,t=60}$ and $R_{mean,t=60}$.

Comparing the different strategies, we can conclude that in the long term "Feeding in drought and post-drought" is more successful in terms of both reserve biomass $R_{mean,t=60}$ (ecological currency characterizing the regeneration ability of the pasture) and herd size $S_{mean,t=60}$ (economic currency) than "Feeding in drought" for all investigated values of mf. Concerning herd size, "Feeding when needed" outcompetes "Feeding in drought and post-drought" when the granted amount mf is high. But note that these results are based on a long-term horizon of 60 years. Analyses have shown that, with a short time horizon of five years, "Feeding when needed" performs better than "Feeding in drought and post-drought" in terms of herd size and only slightly worse in terms of the regeneration ability of the pasture.

From the ecological perspective, "No feeding" (represented by the horizontal line in Figure 4.2) outperforms "Feeding when needed" as well as "Feeding in drought". Additionally, "Feeding in drought" results in even lower herd sizes than without supplementation. Only the novel strategy "Feeding in drought and post-drought"

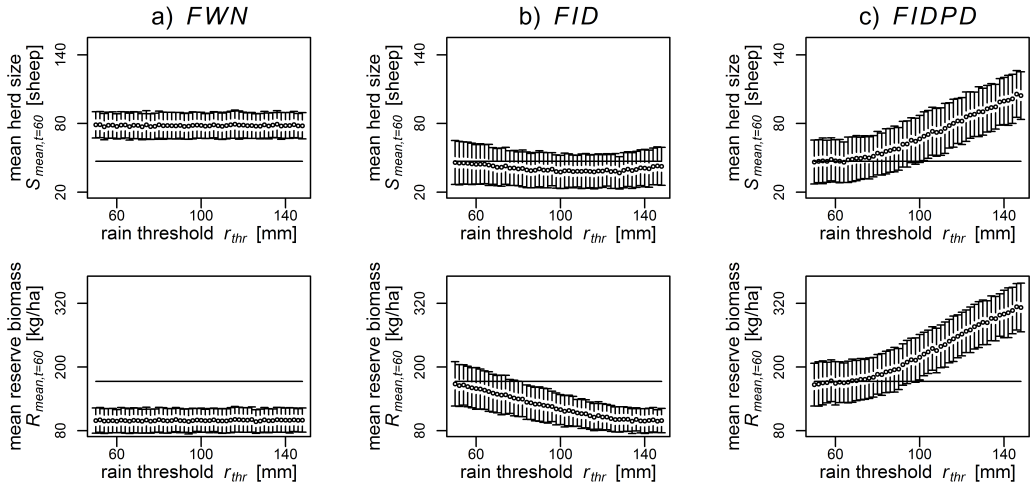

Figure 4.3: Comparison of the different supplementary feeding strategies by the mean herd size $S_{mean,t=60}$ (top row) and mean reserve biomass $R_{mean,t=60}$ (bottom row) in year 60 over 500 simulations for a variation of the rain threshold below which supplements are granted (r_{thr}). The amount of maximal available supplementary fodder mf is set to 50 sheep, the birth rate b to 0.8 and the recovery rate of reserve biomass w to 0.8. The horizontal line indicates the result when no supplementation is granted. Error bars indicate the standard deviation over runs of the according variable. Explanation of abbreviations: "FWN": supplementary feeding when natural forage is not sufficient;"FID": supplementary feeding in drought to avoid destocking; "FIDPD": supplementary feeding in drought to avoid destocking and after supplementation to relieve pasture.

outperforms the strategy "No feeding" in ecological as well as economic terms, especially when supplementation is high.

Figure 4.3 shows the performance of the three supplementary feeding strategies for different values of the rain threshold r_{thr} below which supplements are granted. It highlights a high correlation between the responses of the economic and ecological currencies ($S_{mean,t=60}$ and $R_{mean,t=60}$ respectively) to an increase in r_{thr}, regardless of the strategy type. Of course, varying r_{thr} has no impact on the weather-independent strategy "Feeding when needed" (Figure 4.3a). Since the parameter indicates the amount of annual precipitation below which a year is considered as "dry", higher values result in more frequent subsidies. Of particular note is the negative influence of a higher r_{thr} on both herd size $S_{mean,t=60}$ and reserve biomass $R_{mean,t=60}$ for "Feeding in drought" (Figure 4.3b). While applying "Feeding in drought", herd size is kept at a high level during dry years, resulting in a high pressure on the pasture not only in but also after this critical year. The more frequently pasture is exposed to this pressure, the worse its overall ecological state. An additional resting of the pasture after dry years under "Feeding in drought and post-drought" avoids this effect and hence leads to ecological and economic success (Figure 4.3c).

To grant no supplementation results in a better ecological state in the form of a higher regeneration ability of the pasture than under "Feeding in drought" and "Feeding when needed". Additionally, "Feeding in drought" leads to lower herd sizes and hence to a lower income for the pastoralist. Comparing the novel strategy "Feeding in drought and post-drought" we note that, only for a rainthreshold r_{thr} above approx. 60 mm, "Feeding in drought and post-drought" leads to better ecological and economic conditions than granting no supplementation at all.

4.4.2.1 *Cost-benefit analysis*

In this section, we will perform a cost-benefit analysis for the three supplementary feeding strategies and the case of no supplementation. For this purpose, we evaluate the mean annual net economic benefit $NB_{mean,T=60}$ (i.e., herd size minus subsidy granted by the government) over a time horizon of 60 years. Again, we will assess the impact of the frequency (r_{thr}) and maximum amount (mf) of supplements granted.

Figure 4.4 shows the mean annual net economic benefit $NB_{mean,T=60}$ of the four main supplementary feeding strategies in dependence on the amount (mf) and frequency (r_{thr}) of granted supplements. For "Feeding in drought" (Figure 4.4d), the new evaluation measure $NB_{mean,T=60}$ confirms the observation of the previous section: the influence of mf on the net benefit is low, while a high r_{thr} results in a decrease of the net benefit. For explanation, see previous section. For "Feeding in drought and post-drought" (Figure 4.4b) the observation are only partly confirmed: in contrast to strategy "Feeding in drought" granting subsidies more frequently (higher r_{thr}) leads to high net benefits. However, while herd size is positively correlated with the supplementation amount mf (Figure 4.2c), the net benefit decreases for high amounts of mf. The costs substantially increase with higher amounts of supplements leading to an inefficient cost-benefit balance. Nonetheless, for the whole regarded parameter range, the higher amount of granted subsidies due to the additional granting after dry years does not lower the net benefit below the one of "Feeding in drought". The reason for this is that the strategy "Feeding in drought and post-drought" exploits the natural regeneration capacity of the ecosystem by resting the pasture after dry years. This picture differs for "Feeding when needed" (Figure 4.4c). Here, increasing mf does not result in higher net benefit, as was observed for the herd size $S_{mean,t=60}$ as economic currency (see Figure 4.2), but rather reduces the net benefit. Under "Feeding when needed", there is the danger that the livestock cannot be sufficiently fed by the pasture. This danger increases with increasing amount of supplements mf because this keeps the pressure on the pasture at high levels and leads to stronger decreases in reserve biomass. This causes an increasing dependence on the supplementation with subsidies needed in nearly every year that lowers the net benefit.

Astonishing is the comparison of "No feeding" with the remaining strategies: both "Feeding when needed" and "Feeding in drought" result in lower net benefits than

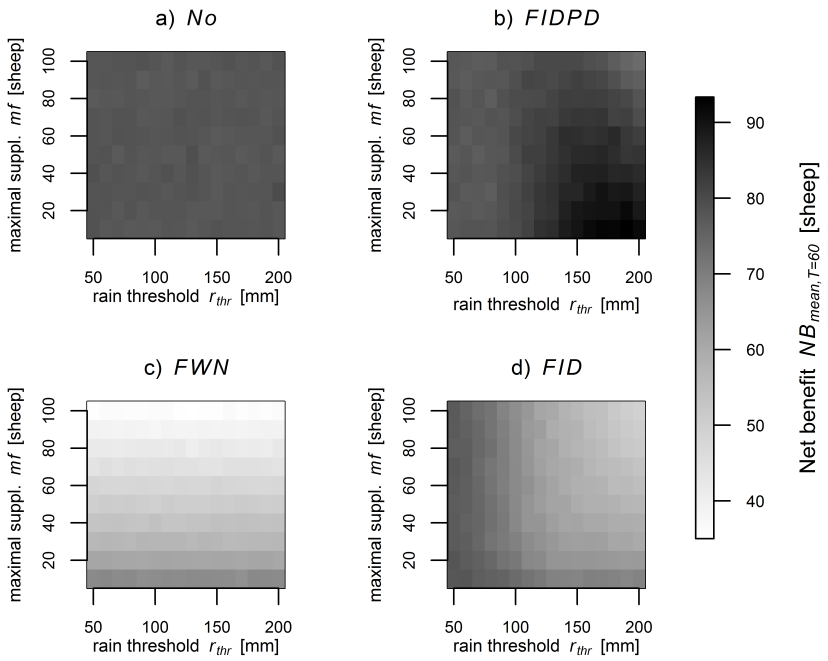

Figure 4.4: Comparison of the mean annual net economic benefit $NB_{mean,T=60}$ (herd size minus subsidy granted from the government) of different supplementary feeding strategies for a variation of the amount of maximal available supplementary fodder (mf) and the rain threshold below which supplements are granted (r_{thr}). The birth rate b is set to 0.8 and the recovery rate of reserve biomass w to 0.8. Explanation of abbreviations: "No": without supplementation; "FWN": supplementary feeding when natural forage is not sufficient; "FID": supplementary feeding in drought to avoid destocking; "FIDPD": supplementary feeding in drought to avoid destocking and after supplementation to relieve pasture.

without supplementation, i.e., the two strategies become counterproductive if supplementation exceeds a critical amount mf. Only "Feeding in drought and post-drought" can significantly outperform the case without supplementation, provided supplementation is not too high but frequent. This indicates the particular importance of the timing of supplementation: if part of the supplementation is used for resting the pasture after dry years, resilience is maintained and savings are made on future supplementation and costs.

4.4.3 *Robustness of evaluation of supplementary feeding strategies*

In this section, we analyze the influence of biophysical characteristics of the vegetation and livestock population's dynamical characteristics on the performance of supplementary feeding strategies. Therefore, we regard the impact of varying a vegetation parameter, the recovery rate w (unitless) of reserve biomass based on green

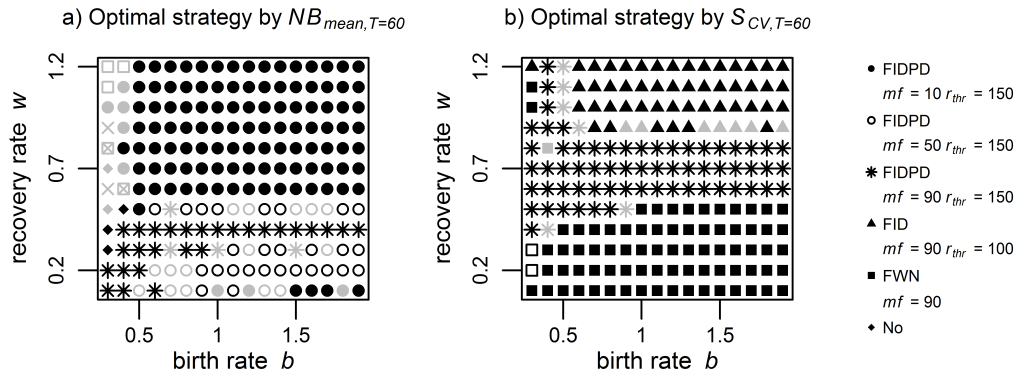

Figure 4.5: Optimal strategy out of the whole strategy space, i.e., the set of the four main strategies each with different management parameter combinations, for different recovery rates of reserve biomass based on available green biomass (w) and birth rates of livestock (b). Optimality is based on a) the highest mean annual net benefit $NB_{mean,T=60}$ (herdsize minus subsidy granted from government) and on b) the lowest coefficient of variation of the farmer's income $S_{CV,T=60}$ over a time horizon of 60 years. Grey dots indicate insignificantly optimal strategies. The legend shows only those strategies that are significantly optimal for at least four parameter combinations of the growth rate w and the birth rate b. Explanation of abbreviations: "No": without supplementation; "FWN": supplementary feeding when natural forage is not sufficient; "FID": supplementary feeding in drought to avoid destocking; "FIDPD": supplementary feeding in drought to avoid destocking and after supplementation to relieve pasture

biomass, combined with the variation of the birthrate of livestock b (unitless). The recovery rate w determines how fast the reserve biomass and so the coping capacity builds up based on available green biomass (see Appendix E).

Figure 4.5 maps the optimal supplementation strategies for different parameter combinations (w, b). In case of optimizing in the sense of maximizing the mean annual net economic benefit (Figure 4.5a), the identified optimal strategies belong to the "Feeding in drought and post-drought" family and merely differ in the degree of intensity. Evidently, strong ($mf = 90$) supplementation is only optimal for a narrow range of medium growth rates w. With a low recovery rate w, reducing the supplementation amount ($mf = 10$ or 50) is optimal because the accumulation of reserve biomass from green biomass left in the current year is hampered. High amounts of supplements in years after a drought to relieve the pasture are not sufficiently used by the pasture due to the low recovery rate w and subsequently financial effort is wasted. In the case of high growth rate w, reducing supplementation amount ($mf = 10$) is also optimal. With higher growth rates, the pasture can already benefit from moderate supplementation. Hence, granting a high amount of supplementation would be economically inefficient.

In case of minimizing the farmer's income variability over the years (Figure 4.5b), "Feeding in drought and post-drought" is optimal for medium recovery rates w of reserve biomass. Supplementation in droughts to avoid destocking reduces decreases in herd size and the additional post-drought resting of the pasture mitigates the decrease in reserve biomass due to grazing over the long run.

For low recovery rates w of reserve biomass, the strategy "Feeding when needed" (instead of "Feeding in drought and post-drought") is found to be optimal. This is due to the fact that the system degrades to a certain extent under "Feeding when needed" when the recovery rate w is low. Subsequently, livestock cannot be sufficiently fed naturally and substantial supplementation is needed in each year. This results in a relatively stable herd size that requires a corresponding amount of supplementation and therewith also costs. Under the "Feeding in drought and post-drought" strategy, degradation can be avoided due to resting of the pasture, but livestock numbers vary with natural variation in available biomass. Therefore, "Feeding in drought and post-drought" leads to higher variability in income than "Feeding when needed".

For high recovery rates w of the reserve biomass, the strategy "Feeding in drought" is found to be optimal. For high growth rate w, supplementation after droughts to relieve the pasture under "Feeding in drought and post-drought" leads to high biomass peaks. These could then be followed by proportionally high decreases in herd sizes in subsequent years when supplementation is not granted (due to the precipitation condition). Under the "Feeding in drought" strategy, the variability in reserve biomass is not as high because here the supplements are not used to rest the pasture. Additionally, "Feeding in drought" does not lead to strong decreases of reserve biomass over the 60 years when the recovery rate w is high. This leads to the lower income variability of "Feeding in drought" for high recovery rates of the reserve biomass (upper area in Figure 4.5b).

4.5 DISCUSSION

The main aim of this paper was to assess the cost-efficiency performance of government supplementary feeding programs implemented in many pastoral regions in drylands for instance in North Africa and West Asia (Hazell, 2000, p. 93), or as part of development projects (cf. the Project of Pastoral Development and Livestock in the Oriental PDPEO in Morocco, Mahdi (2007)). These programs are usually introduced by governments in response to multiple climate-related societal challenges such as poverty alleviation, value addition or maintenance of resilient pastures. Therefore, it was important to assess the government supplementation programs from a multi-criteria perspective and also to apply a cost-benefit approach.

Supplementary feeding is intensely debated. On the one hand, it is acknowledged as strategy for keeping livestock numbers stable under fluctuating environmental conditions (Horn et al., 2002). On the other hand, negative effects such

as degradation caused by the decoupling of vegetation-livestock dynamics are also being discussed (Illius and O'Connor, 1999; van de Koppel and Rietkerk, 2000; Le Houerou, 2000; Richardson et al., 2005; Vetter et al., 2005; Bourbouze, 2006; Teague et al., 2009; Diaz-Solis et al., 2006). The present study was based on the hypothesis that potential benefits and threats of supplementation strongly depend on both the specific design of the supplementation strategies and the characteristics of the regional context. This was extrapolated from a similar study on potential benefits and threats of novel technologies and institutions on rangeland systems (Müller et al., 2011). Therefore, we systematically assessed the performance of 21 supplementation strategies that differ in terms of the way supplements are used as well as the timing, frequency and intensity of supplementation, compared them to each other and to the case without supplementation as reference, and assessed the robustness of the findings to various contexts.

4.5.1 *Key factors determining the benefits and threats of supplementary feeding*

Our model results indicate that supplementary feeding is not automatically advantageous or disadvantageous. We found that there are two key factors that determine potential benefits and threats: the timing of supplementation (i.e., weather-independent or in/after dry years) and the way in which supplemented fodder is utilized (i.e., to avoid destocking or to rest the pasture):

1. As long as supplementation is provided at each time of fodder shortage (cf. strategy "Feeding when needed"), the herd size can be stabilized, but only at the cost of a decreased ecological state of the pasture, increasing dependence of pastoral livelihood on the supplementation and high costs to the government and society.

2. If the provision of supplementation is restricted to certain environmental conditions (here: weather conditions such as the amount of precipitation), the timing and the way in which supplements are used are crucially important. Supplementation can cause the ecological and economic situation to improve or deteriorate, depending on how supplements are used.

3. A cost-efficient improvement of the ecological, economic and social benefits can be attained if supplementation is provided in years of drought and the years after (cf. strategy "Feeding in drought and post-drought") to avoid destocking (in the years of drought) and to give the pasture time to recover (in the years after). In doing so, choosing the appropriate amount of supplements is crucial for successful implementation of the strategy "Feeding in drought and post-drought" because excessive supplementary feeding carries the risk of economic inefficiency. The importance of using part of the supplementation to regenerate the pastures in post-drought years is illustrated by a comparison with the analysis of the "Feeding in drought" strategy, where

supplements are used only to avoid destocking in droughts. This strategy is found to be counterproductive and even worse than no supplementation at all due to the stronger deterioration in the ecological state of the pasture. The same applies to the strategy "Feeding when needed" where supplements are granted whenever needed, irrespective of precipitation. Due to high grazing pressure and the absence of vegetation resting periods, these strategies lead to deterioration in the ecological state of the pasture in our study. These findings are in line with Hazell (2000) and Linstädter et al. (2010, 2013) who argue that supplementation may lead to overgrazing due to a weakened environmental feedback as livestock numbers are decoupled from the presence of natural vegetation. It should be noted that while those conventional strategies are not recommendable from an ecological and a long-term economic perspective, they do help to reduce income risk and are hence widely applied. Under the novel strategy "Feeding in drought and post-drought" investing in the reserve biomass reduces the demand for supplementation (and so societal costs) as the enhanced resilience supports the pasture in providing fodder naturally. Under "Feeding in drought and post-drought", supplementation builds up natural capital and is therefore synergistic. This is in line with Müller et al. (2007) and Müller et al. (2015) who showed that ensuring resting is crucial for sustainability in pastoral systems and represents an "ecological insurance" which benefits the ecological and economic performance.

4. The relevance of supplementation as source of economic and social benefits also depends on the regional context (in this study the biophysical characteristics of the vegetation as well as the livestock population dynamics). If the birth rate of the livestock is low, the benefits of supplementation and the differences between the strategies are indifferent and occasionally even outcompeted by the case without supplementation. With low livestock birth rates, the herd size cannot sufficiently benefit from supplementation and the pastures already recover due to unplanned resting. In this case, supplementation is not profitable. Additionally, if the recovery rate of the vegetation is low, high amounts of supplements in years after a drought to relieve the pasture are not sufficiently used. Therefore, the intensity (i.e., amount of granted supplements) of this strategy ought to be adapted to the recovery rate of the reserve biomass. Furthermore, excessive supplementation is also inefficient when the recovery rate of the vegetation is high because the pasture can already benefit substantially from moderate amounts of supplementation. In terms of income variability, the novel strategy "Feeding in drought and post-drought" is beneficial if recovery rate of the vegetation is medium. These effects show that government supplementation programs are only cost-efficient if they are regionalized and adapted to the ecological characteristics of the rangeland utilization system. The environmental context influences potential benefits and threats of the supplementation programs. This is relevant for the question of robustness

and transferability of findings and for the adaptation of a supplementation program to the context settings.

4.5.2 *The management of individual income risks and societal costs*

We provided insight into the functioning of different mechanisms of reducing climate-related income risks of the individual pastoral households (social benefit). We have shown that there are two principle ways in meeting this goal: using "Feeding in drought and post-drought", but also using "Feeding when needed". In the latter case, the income risk is reduced through frequent supplements, i.e., always when needed independent from the precipitation. This is realized at the cost of the government and society because the individual households do not bear the cost of supplementation, it is all subsidized by the government. This is seen also in reality, for example, in many West Asia and North Africa countries where supplementary fodder is granted permanently, leading to high expenditure of public resources for the distribution of subsidized fodder (Pratt et al., 1997; Hazell and Hess, 2010). In our study, this shows that "Feeding when needed" reduces the individual risk (income risk) at the expense of increasing societal costs for the supplements. In contrast to this, "Feeding in drought and post-drought" partly invests in maintaining the reserve biomass and so the resilience of the pasture. In this case, the intended stabilization of the pastoralist's herd size and income can be achieved through benefiting from the enhanced puffer capacity of the pasture (cf. Müller et al., 2007; Quaas et al., 2007) that saves future societal monetary resources. As the result, the individual income risk is mitigated instead of just being shifted to another societal group. These results show the benefits of an appropriate sustainable management of ecosystems as natural capital and the socio-economic relevance of enhancing resilience (here of the pasture by the provision of sufficient reserve biomass). They demonstrate why it was useful to integrate resilience in the Total Economic Value concept underlying the TEEB study (The Economics of Ecosystems and Biodiversity (TEEB, 2010)).

Furthermore, the comparison of the supplementary strategies "Feeding when needed" and "Feeding in drought and post-drought" underpins the importance of explicitly accounting for the costs of government supplementation programs. We have seen that cost-benefit relationships strongly depend on the design (way how supplements are used, timing, frequency, intensity) of the supplementation strategies and so the structure of the social-ecological feedbacks in the pastoral resource utilization system. Without explicitly considering costs, the "Feeding when needed" strategy would have been rated higher and an important societal problem (cost-inefficiency) would have been overlooked. In contrast, the consideration of costs revealed that the "Feeding in drought and post-drought" strategy increases the net benefit compared to the currently practiced strategies "Feeding when needed" and "Feeding in drought", while not leading to substantially higher total costs of supplementation. The "Feeding in drought and post-drought" strategy exploits the natural capacity of

the ecosystem by resting the pasture after dry years. Despite its advantages in terms of net economic benefit, the "Feeding in drought and post-drought" strategy leads to substantially higher costs than granting no supplementation. The appropriateness of this strategy, therefore, also needs to be evaluated in the regional policy context as it strongly depends on the grantor's financial capacity. Hence, we are not suggesting that supplementation should be introduced, but rather where government funds are used for supplementation, pasture resting after droughts should be incorporated. However, other risk management strategies such as mobility should also be investigated as possible alternatives to supplementary feeding (see Section 4.5.3 Future research tasks).

Müller et al. (2015) have assessed the performance of a range of supplementation strategies that have to be privately financed by the pastoral households themselves (in contrast to the government financing assumed in the present study). Although the two studies differ with regard to the assumed mechanisms of financing, they come to similar conclusions. In Müller et al. (2015) low costs are of high importance for the pastoralists. A long-term thinking farmer selects supplementation strategies which strengthen the resilience of the pasture so that his herd size and income are stabilized in a natural way and degradation and cost explosions are avoided. In the case of government financing, as assumed in the present study, the cost-efficiency requirement means that strategies which improve the resilience of the pasture and are not only of ecological and economic but also of social benefit will be deemed optimal. Note, however, that this assumes long-term thinking government agencies which in reality might not always be the case.

In summary, our results underline the importance of considering individual as well as collective benefits, and of ensuring pasture regeneration when designing risk management strategies. Therewith, this study contributes to the debate on one of the most pressing challenges in the field of earth system science, the support of global sustainability (ICSU, 2010; Reid et al., 2010). In this debate, it was claimed that an appropriate design of institutions is needed to enable progress on global sustainability by, for example, harmonizing individual and collective benefits or supporting poverty alleviation. The same is true for the development of strategies for managing disruptive global environmental change, where enhancing resilience is crucial. The present study shows by way of example that modeling can make an important contribution to mastering these tasks.

4.5.3 *Future research tasks*

While aiming at multiple goals (i.e., mitigation of climate risk, poverty alleviation), supplementation strategies may also have negative side effects. For example, in this study, we showed that conventional supplementation strategies may lead to degradation. Hazell (2000, p. 93) state that supplementary feeding strategies "have a tendency to become permanent". The increased resource need for supplementation

encourages cultivation of barley on land originally used as rangeland (Hazell and Hess, 2010). Although this effect was not investigated in our study, this could diminish the performance of the so far successful strategy "Feeding in drought and post-drought".

Therefore, future research should compare supplementary feeding strategies to other risk management strategies as well. This was not done in the present study because focusing on supplementary feeding strategies fostered a thorough system understanding. Future research could adapt the applied model to investigate the effect of supplementary feeding also in combination with further risk management strategies. These should include traditional strategies based on local knowledge (e.g., mobility strategies, grazing reserves for times of drought, social networks or mixed livestock and crop production (Ahmed et al., 2002; Müller et al., 2007; Okayasu et al., 2010; Martin et al., 2014; Silvestri et al., 2012; Zampaligre et al., 2014)). In addition, further formal strategies, such as weather or other index-based insurances (Rota and Sperandini, 2009; FAO, 2010), should be incorporated into the evaluation of supplementary feeding strategies. Extrapolating from knowledge derived from the present model, we hypothesize that including further strategies such as mobility or cooperative grazing strategies into our model would highlight the importance of resting pastures in general. However, further research is needed to gain more concrete insights and to identify possible unpredictable side effects.

Further simplifications include the assumption that the pastoralist has perfect knowledge about the forage availability in the upcoming year. Assuming limited knowledge would require including uncertainty aspects in the stocking decision. In the current model version with only one time step per year, this could have two different effects: overstocking would not change the model results because animals would simply be sold at a later point in the year, understocking would have a positive effect on biomass. In addition, we assume a single household owning a homogeneous herd. Thereby, we neglect the practice of keeping herds consisting of animal species with different drought sensitivities. This may mitigate the decrease in herd size due to natural forage shortage in droughts and hence impede recovery phases of the pasture in these years. We hypothesize that this would even strengthen one of our main model results: the importance of using supplements to rest the pasture.

Finally, the ecological submodel for simulating vegetation dynamics was kept simple. For example, we assumed a constant mortality of reserve biomass that is independent from precipitation. In contrast, empirical studies showed increased plant mortality due to consecutive low-rainfall months and droughts in drylands (e.g., Milton and Dean, 2000; Hodgkinson and Muller, 2005). Hodgkinson and Muller (2005) found that these impacts depend on intra-annual rainfall patterns and vary over space - characteristics that are not depicted in our model. In combination with grazing effects, such drought impacts become even more complex and are still uncertain (Hodgkinson and Muller, 2005).

4.6 CONCLUSION

Based on insights from our ecological-economic model, we recommend that if governments grant supplementation, resting of the pasture after droughts should be incorporated. This will ensure economic benefit for the individual pastoral household while at the same time ensuring that strategic government goals such as poverty alleviation or the preservation of resilient pastures can be met cost-efficiently. However, further research should also compare supplementary feeding strategies to other risk-coping strategies. Furthermore, the hypothesis developed on the basis of our ecological–economic model should be tested in field experiments and the appropriateness of novel risk-coping strategies should be discussed with practitioners.

Part III

ENVIRONMENTAL EDUCATION AND COMMUNICATION

5

DESIGN, IMPLEMENTATION AND TEST OF A SERIOUS ONLINE GAME FOR EXPLORING COMPLEX RELATIONSHIPS OF SUSTAINABLE LAND MANAGEMENT AND HUMAN WELL-BEING

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5.1 ABSTRACT

Land is a limited resource providing various services. Decisions on land use shape the distribution of these life support functions and thus require understanding of complex feedbacks between decisions on land use and human resource appropriation. Due to multiple nonlinear feedbacks between management, productivity, environmental quality and human well-being, complexity is an inherent property of land systems. We present an educational game, which aims at illustrating options of sustainable land management to the interested public, students and stakeholders. The game provides the opportunity to govern a country by exploring how contrasting dimensions of sustainability (economy, environment and social conditions) can be harmonized regionally, while continuously being threatened by global trade fluctuations. The game was tested by several groups of students from high schools and universities. The feedback shows that the game is a valuable tool in environmental education initiating learning the complexity of feedbacks in land use and resources appropriation.

5.2 INTRODUCTION

Sustainable land management is among the grand challenges of the next decades (Foley et al., 2011; Garnett et al., 2013). Multiple requirements, such as production of food and energy, provision of space for living and infrastructure or maintenance of ecosystem function and biodiversity, put high pressure on the limited land resources. Land use management of a given region has to fulfill criteria of sustainability with respect to environmental, economic and social performance. Simultaneously, fulfilling all requirements of sustainability has to be achieved while maintaining ecosystem services and biodiversity (Tscharntke et al., 2012). Understanding landscapes with their multi-functionality increases complexity of feedbacks to be considered, but also provides opportunities for solutions in sustainable land management (Seppelt et al., 2009). Although regionally focused, land management strongly depends on global trends. Management decisions on land use on a local or regional scale can have off-site or external effects, which might remain unconsidered if solely focusing on land management in a region of interest (Seppelt et al., 2011, 2013). One approach to manage land more sustainably involves the integration of stakeholders from the beginning of planning processes (Voinov and Bousquet, 2010) and may lead to sophisticated decision support tools as result (see for example McIntosh et al. (2011); Oxley et al. (2004); Volk et al. (2010)). As the matter of sustainable land management concerns our society as a whole, it is important to increase public awareness and understanding of this concept.

Among different didactic tools for raising awareness of environmental questions, serious games form an innovative strand, which gains more and more attention (Barreteau et al., 2007). Here, we present a newly developed computer game enti-

tled LandYOUs, which increases an understanding of the challenges in sustainable land management among pupils and students from the age of 14, interested public and stakeholders from land management. In an interactive and entertaining way, players learn about the complex interplay of economic, social and ecological aspects, and the impacts of land management on human well-being and nature conservation. Thus, LandYOUs aims at bridging the gap between landscape modeling and environmental education. A system dynamics model of LandYOUs simulates the complex feedbacks and interrelations of land systems management. The game serves as a training tool, which encourages systems thinking and discovering the nature of nonlinear cause-effect relations. The LandYOUs serious online game has been launched in 2013. This study presents the concept and implementation of LandYOUs, as well as the evaluation of the first user survey. Finally, further improvements and utilization of LandYOUs are discussed.

5.3 CONCEPTS OF SERIOUS GAMES IN ENVIRONMENTAL EDUCATION

Games represent valuable tools for communication and educational purposes. They provide an easy transmission of complex and serious topics by increasing players' motivation and interest to understand them. Crookall (2011) provides an overview of the recent development of simulations and games, and strengthens the importance of serious games. Garris et al. (2002) suggests that one of the reasons why serious games receive an increasing attention is the shift in the field of learning: from a traditional approach to a "learner-centered model", in which learners take an active role in the educational process instead of being pure recipients. Eisenack (2012) points out that the effect of "positive connotation" of games helps achieving the educational purpose. Multiple studies investigate the effectiveness of games for educational purposes. For instance, Virvou et al. (2005) show the effectiveness of the VR-ENGAGE educational software with a gaming aspect particularly for students who show a poor performance in the domain taught prior to their learning experience with the game. Gosen and Washbush (2004) provide a summary of exemplary studies evaluating the success of simulation and gaming. The authors list several empirical studies advocating the experiential learning as an effective approach. At the same time, they point out that these results should be treated with caution, and emphasize the importance of enhancement of consistent validation standards for experimental learning methods.

Various games with educational purpose have been recently developed in the environmental field. KEEP COOL is a board game focused on aspects of climate change (Eisenack, 2012). In FUTURE VOLTAGE, the player controls the electric power supply system (Benders and Devries, 1989). Fish Banks (1989), another well-known example of an online game, which is based on the original board game version, is addressing the topic of renewable resource management. The ÖKOLOPOLY® board game from 1978, a pioneer among environmental educational games, was

using system dynamics as underlying simulation model. This board game was later transformed into the computer game ECOPOLICY® (Vester, 1984)[1].

Ulrich (1997) provides an extensive survey on simulation games within the field of environment and sustainability. The author's results showed that combination of high quality content and design with a proper administration of simulation games (such as provision of supplementary material, background information or alternative languages) supports the effectiveness of games in environmental education.

These findings were very helpful during the development of LandYOUs, which has the following core idea: players step into the role of a governor who controls the land use of a virtual country by various capital investments. Rather than quantitative processes, the game focuses on qualitative processes of land management, as in the KEEP COOL board game (Eisenack, 2012) or ECOPOLICY® (Vester, 1984). LandYOUs was designed as a serious online game for three main reasons. First, it can be quickly distributed to a wide public and thus allows a fast and effective communication of complex issues of land management. Second, computer games allow direct incorporation of complex system dynamics and, thus, are particularly suitable for the field of land use management. Thirdly, it allows the use and application without any limitations on licenses or other restrictions. It is therefore suitable to initiate discussions on the topic sustainable land management at various locations and situations. LandYOUs was designed to offer an appealing graphical user interface to positively affect the gaming experience and support learning.

5.4 MODEL CONCEPT AND IMPLEMENTATION

5.4.1 *Overview*

After starting the game, the graphical user interface with the main elements is displayed: the land use map, indicator panels with feedback relationships, policy investment controls, and various interactive help and annotations options (for GUI, see Section 5.4.4). At the same time all initialization procedures are executed (see Appendix F Section F.7.1). In each out of ten rounds maximum, the player then decides on investments in any combinations of measures on agriculture, afforestation, settlements, nature conservation or education, see Appendix F Section F.7.2. Based on these investments, land use changes are estimated; feedbacks to all other indicators within a nonlinear discrete dynamic system are evaluated; the users score is estimated; and the new budget is calculated, see Appendix F Section F.7.3-F.7.6 and below.

The underlying model links decisions on five policy measures with spatially explicit land use change and a dynamic feedback system that characterizes the socio-environmental system.

1 http://www.frederic-vester.de/deu/ecopolicy/

5.4.2 *Purpose and basic principle of the model*

To demonstrate various options and feedbacks of land management decisions, the core function of the underlying model of the game LandYOUs is to provide an aggregated system dynamics model with a reduced number of state variables, which get input from a spatially explicit map representing land use. Although very much aggregated, the model should be capable of qualitatively capturing real world patterns, e.g., reproducing reasonable patterns according to Grimm et al. (2005). The model underlying LandYOUs is implemented as time-discrete system dynamics model. It is complemented by a spatially explicit landscape represented by cells in a regular grid. The spatial explicitness of the model allows incorporating aspects of landscape configuration. The feedbacks between various indicators are calculated by nonlinear functions, which are coded in accordance with findings from recent literature. For details on specific relationships see Appendix F Section F.7.5.

Being the basis for an educational game comes along with requirements for the underlying model. To support the player's perception and understanding of state variables, indicators in the model are normalized (range between 0 and 10). Hence, the feedbacks do not correspond with quantitative representations of the real world. Therefore, the underlying model of LandYOUs cannot be tested against real world data, as documented by Bennett et al. (2013). However, the model captures real world feedbacks in a realistic way and reproduces qualitative relationships as required by Grimm et al. (2005).

For an exciting gaming experience, variations between games should be ensured. Therefore, several random processes are incorporated in the model. For example, deviations of the market price randomly occur over the 10 rounds. Thereby, sudden changes in global markets and their impact on the national economy are incorporated into the game.

5.4.3 *Model and game elements*

Figure 5.1 illustrates this conceptual model, which is implemented as time-discrete system dynamics model, where each round resembles approximately 5 years of governance.

Functional relationships between the landscape map and the indicators as well as between the indicators themselves reflect complex interdependencies of various aspects. The indicators, which set up the nonlinear time-discrete dynamics, are:

- Agricultural production,
- Environmental quality,
- Quality of life,
- Education,

- Consumption,
- Population,
- Financial resources and
- People's needs,

which are calculated for each round, representing responses of the dynamic system and describe the social, ecological and economic situation of the country.

Three of these indicators, namely agricultural production, environmental quality, quality of life, depend on the landscape, its composition and configuration. The map of the landscape consists of cells in a regular grid, which can be assigned to different land covers:

- Water bodies,
- Cropland,
- Forest,
- Settlement,
- Fallow land and
- Nature reserves.

Except cells representing water bodies, which cannot be changed during the game, and settlements, which can grow but not shrink, all others are subject to land use changes. Each cell is characterized by properties (such as fertility and productivity). Moreover, land use configuration (neighborhood and distances) is used for calculation of indicator values. Various ecosystem functions, such as provisioning of pollination service for agriculture provided by forest edge habitat or environmental quality due to heterogeneity of the landscape, depend on the configuration of the landscapes. Therefore, cell properties, such as productivity, are influenced by neighborhood effects, prior use and site-specific conditions (e.g., fertility). Thus, the broad categories, that characterize the landscape, capture not only land cover but also land use and site-specific characteristic of use. The indicator values of

- Agricultural and forest production,
- Environmental quality and
- Quality of life

are used to calculate players' score and provide an indicator for achieving sustainability (see Appendix F Section F.7.6).

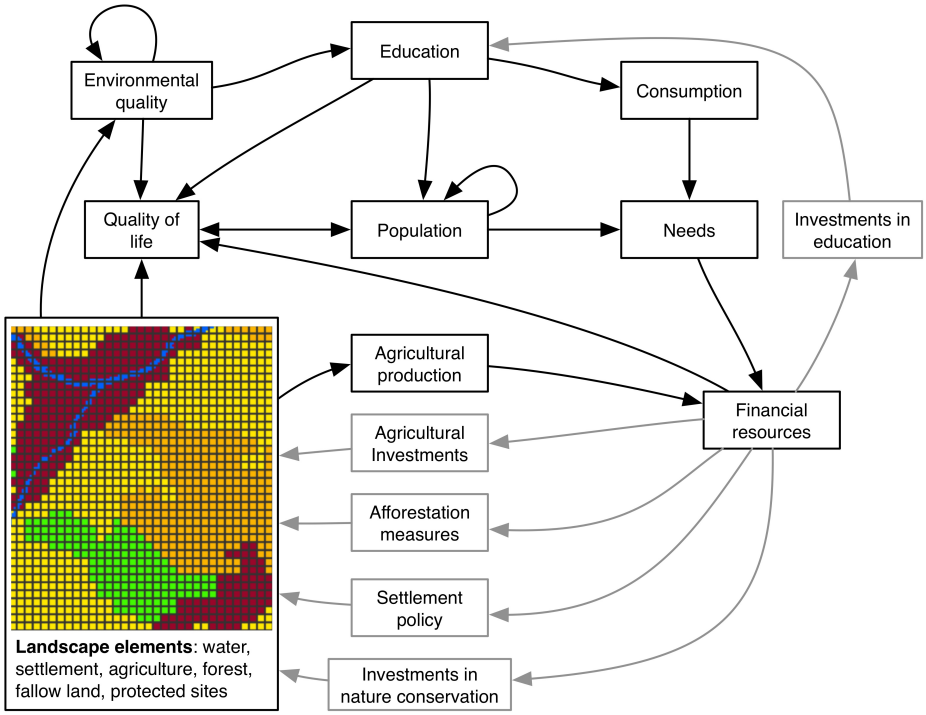

Figure 5.1: Illustration of the feedback system. The state variables or indicators are plotted in black, investments and their impacts on the state variables in gray. The state variables of agricultural production, environmental quality and quality of life are derived from the spatially explicit configuration of the landscape elements (water, agriculture, forest, settlement, fallow land and protected sites) represented by cells in a regular grid.

5.4.4 *Land use change and system dynamics*

System dynamics and spatial explicit land use change are processed in four steps: (1) changes in land use, (2) translation of land use pattern and land use change to indicator values, (3) feedbacks between indicators and (4) external effects caused by global markets.

1. Land use change is primarily driven by the investment decisions of the player, but also by the market and the current population size. Expansion of settlement areas for instance is due to increasing population size. The degree of expansion can be controlled by investments in settlement policies as these increase the number of people that can live in a given settlement area. Investments in nature conservation increase the area of nature reserves within the landscape. Finally, the shares of agricultural land, forests and fallow land are determined by the financial support of agriculture and forestry, and the current market prices. At this, land use change concerning agricultural production and forestry is based on the concept of profit maximization. For this,

market prices in the model are determined by supply and demand, a standard assumption in economic theory (Mankiw and Taylor, 2006).

2. The land use map is used as the base for determining agricultural production, environmental quality and quality of life. The amount of produced agricultural products is estimated from the total area of agricultural land and its condition, influenced by prior uses and configuration of the land. For example, nature conservation areas adjacent to agricultural land positively influence the agricultural production due to the provided ecosystem services such as pollination (Lautenbach et al., 2012; Klein et al., 2003). Similarly, land use configuration influences the environmental quality. For instance, an intensive agricultural production adversely affects the adjacent protected sites due to the utilization of fertilizers. Furthermore, these areas are negatively influenced by the extent of settlements due to traffic noise, soil sealing and emissions. Besides effects of landscape configurations, the total area of protected sites, forests and fallows positively influences the environmental quality. Finally, the 'quality of life' indicator is determined by evaluating the surroundings of the settlement areas: forests and protected sites near settlements positively influence quality of life. Unlike the three indicators that depend on land use and configuration (agricultural production, environmental quality, quality of life), the indicator of education is directly influenced by investments in education. All remaining indicators are calculated based on the feedbacks within the set of indicators.

3. The feedbacks between various indicators are calculated by mostly nonlinear functions, which are coded in accordance with the findings from recent literature. For details on specific relationships, see Appendix F Section F.7.5.

4. After all indicators have been calculated, possible external effects, e.g., trade with regions outside the governed country, are taken into account by computing surplus or lack of agricultural products, which then determines possible export or import. Costs for imports or revenues from exports depend on the global food market. In three out of ten rounds of the game the market price is randomly increased or decreased by up to 100%. Hereby, sudden changes in global markets and their impact on the national economy are incorporated into the game. Thus the player experiences global market developments and needs to adapt to changes with his/her local and regional decisions. On the other hand, we assume that the effects of the players' decision on the global market of agricultural products are comparably low, and an impact of regional agricultural prices is negligible.

5.4.5 *IT design of LandYOUs based on GISCAME framework*

The LandYOUs online computer game is implemented based on the GISCAME framework, which provides a three-tier architecture: the core calculation framework, the

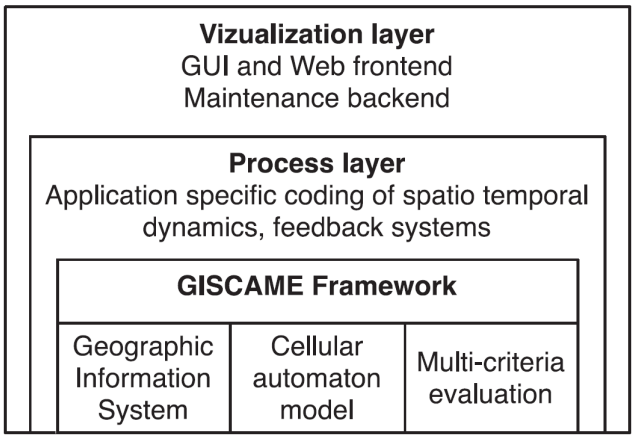

Figure 5.2: Three-layer architecture of the GISCAME framework. Based on the GISCAME core framework with the functionality of a geographic information system, cellular automaton models and a multi-criteria evaluation, an application specific rule based system implements the spatio-temporal feedbacks of LandYOUs. The independent visualization layer compiles results appropriately, displays results according to illustrations and design features, and provides the web frontend as well as backend for maintenance.

process layer and the visualization layer (Fürst et al., 2010a). This modularity allows the GISCAME framework to be used as a decision support system, in university education or in several international research projects[2]. Furthermore, it serves as a core implementation system for several online computer games in environmental education, such as PIMP YOUR LANDSCAPE[3] or FORESTER[4].

LandYOUs makes use of all elements of the GISCAME framework, see Figure 5.2. The core framework performs the simulation and evaluation of trends initiated by land use changes. It combines a cellular automaton model, geoinformation system features and multi-criteria assessment functions (Fürst et al., 2010b, 2013). In LandYOUs, a landscape is coded as an area of a fixed number of grid cells. GISCAME allows each cell to be assigned several attributes, e.g., land use or productivity, see Section 5.4.3.

The process layer is a game specific and configurable rule system. Linking GISCAME with specified rules enables to display interrelations of the user investment choices and the cells. These interactions determine the indicators described in Section 5.4.3. The specified rules are described in the LandYOUs interface rule system, which interlinks GISCAME and the graphical user interface (GUI) of the game.

The visualization layer translates the results of the simulation to the GUI, which is implemented in HTML, Javascript and PHP. The modular and flexible implemen-

2 www.giscame.com
3 http://www.letsmap.de/letsmap/die_spiele_pimp_your_landscape.html
4 http://www.letsmap.de/letsmap/die_spiele_forester.html

tation of LandYOUs and its underlying GISCAME framework enables modification of model parameters by an administrator through the maintenance backend.

5.4.6 *Design of the graphical user interface*

The LandYOUs game was developed to give a broad target group (namely students and pupils, interested public, stakeholders) an understanding of sustainable land management. The game design should therefore be attractive for all user groups, regardless of their age. Here, we summarize key aspects from the user interface and recommend visiting the game's web page for in-depth experiences[5].

The developed graphic design emphasizes the serious character of the game. Besides the task of developing an attractive graphic design, the second main objective was to illustrate the complex interrelations between the landscape and the indicators on sustainable land use in one GUI: all main elements of the game, such as interaction controls or informational text fields, should be visible at any time. Furthermore, the GUI offers an interactive feedback system, which provides help based on the current course of the game. Figure 5.3 shows the GUI consisting of five sections: (1) the land use map, (2) the indicators with their feedbacks, (3) the policy investment controls, (4) the evaluation button and (5, A-D) the interactive help and annotations.

The land use map with a legend (Figure 5.3, Label "1") illustrates the current land use configuration, which affects various indicator functions. To visualize the player-driven changes, the map is recalculated by the core system in each game round, i.e., in each time step. Maps of the previous rounds can be accessed (see the number range in the lower right corner of the map). With this, the player can reveal the consequences of his/her decisions and the resulting land use changes. With the five policy investment controls below the map (Figure 5.3, Label "3"), the player decides on investments to govern the country and triggers changes of the map and the indicators.

The complex system of indicator functions and their interrelations is shown in a simplified scheme next to the map (Figure 5.3, Label "2"). Each indicator is represented by a green box or label. Each label displays the indicator name. A chart in the center of each box shows the temporal changes of each indicator (Figure 5.3, Label "B"). These time-series graphs of the indicators values offer an in-depth analysis of the dynamic patterns. A set of icons explain which policy options influence the particular indicator (Figure 5.3, Label "A"). Additionally, a signal light (red, yellow or green) supports assessing the current status of a given indicator (Figure 5.3, Label "C"). The overall game score is displayed as a pie chart, where different segments represent the core indicators of sustainability: environmental quality, financial resources and quality of life, see Appendix F Section F.7.6.

5 www.landyous.org

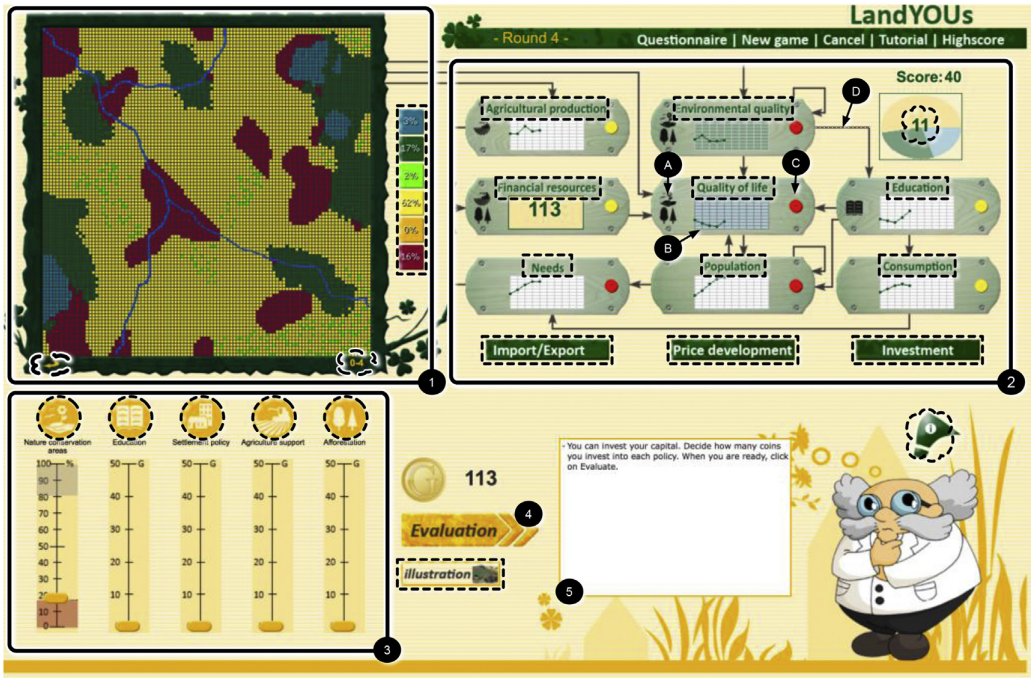

Figure 5.3: LandYOUs main screen with (1) the land use map (top left), (2) the feedback system, (3) the decision-making sliders, (4) the evaluation button and (5) the info box of "Prof. Landstein" (a guide through the game). Dashed lines denote active regions of the screen, which reveal more information when clicked. All icons of the dynamic system indicators contain information about (A) policy options that affect them, (B) the recent trend, and (C) the current status visualized as signal light. Further information on the feedbacks is provided by clicking on the arrows (D).

Besides this more technical or scientific way of displaying the current state of the socio-environmental land use system, the status is illustrated by a landscape picture. The picture merges various cartoon-like illustrations that capture the main indicator values (Figure 5.4). Within individual sections of this landscape picture, the status of indicators of environmental quality, productivity, consumption, available capital, population size, education and quality of life is translated and illustrated with dynamically generated subpictures. Different sections of the landscape picture can be clicked and text with further information and explanations of the current indicator status as well as the changes in the last round is obtained.

The landscape picture thus supports interpretation of results and understanding of changes caused by previous decisions on land management. In addition to this result-related feedback, the GUI also offers an action-related feedback by the presence of a guiding figure named "Prof. Landstein", which serves as a narrative medium. It is an illustrated cartoon mascot that accompanies the player during the game and facilitates a direct and personal communication.

Figure 5.4: Four different illustrations of the possible conditions in the country of LandYOUs. These pictures are merged cartoons, in which every section illustrates the status of an indicator of the country in a given round, translating its raw value into a cartoon. As an example, these illustrations show various situations during the game: high population density, high agricultural productivity, sufficient environmental status and monetary resources (upper row), or lower population density and low or very low agricultural productivity (lower row). Consumption changes from low (left column) to medium and partly wasteful or high consumption (right column).

LandYOUs also provides an elaborated concept on providing help and supportive information. A tutorial explains possible steps during the game and describes interactive interface elements. Further definitions and background information, which provide additional help to understand the content of the game, are available in small information windows that pop-up when clicking on active regions of the GUI, in Figure 5.3 illustrated by dashed lines.

5.5 APPLICATION AND RESULTS

5.5.1 *How to play?*

Each LandYOUs game starts with low to average indicator values, mimicking critical situations for the considered dimensions of sustainability, such as economy, human well-being and the environment, see Appendix F Table F.2. By investing capital in

different policy options, the player determines land use change and modifies indicators. The objective of the game is to achieve a balance between social, ecological and economic conditions, e.g., closer approach sustainability. To achieve this goal, the player has to carefully observe changes of the indicators and the land use map in each round of the game. Furthermore, the player may study additional information provided as help text and comments from "Prof. Landstein". Financial resources increase or decrease based on the profit obtained from agricultural production and determine opportunities for management decisions in the next round. A successful strategy results in a high number of score points collected after each round. Score point calculation takes into account the current states of financial resources, environmental quality and quality of life (see Appendix F Section F.7.6).

Investments in education at an early stage of the game play a major role in achieving a good environmental and life quality. High education keeps the population size at a moderate level and thereby also enables moderate consumption. As a consequence, there is no need to increase the extent of agricultural land. Moreover, the agricultural products that are beyond regional demand can be profitably exported. Thus, there is enough space left to preserve nature and a good environmental quality. Successful strategies regulate social, ecological and economic indicators simultaneously. In contrast, weak strategies may lead to overpopulation and imbalanced land use with either too low or too high production. When players bring the indicators of environmental quality or quality of life to the lowest values, the game ends prematurely.

5.5.2 *Survey feedback*

Evaluating and testing a game like LandYOUs is different compared to testing a mere environmental model (Bennett et al., 2013). Besides being scientifically sound and robust, the game requires a feedback from user community. Therefore, we conducted an online survey among the first users of the game. When testing the first version of the game, two questions were examined:

1. Was the game attractive enough to keep people interested in playing over the desired time? Does the game offer a possibility of exploring (most of) all possible feedbacks and patterns?

2. How did players feel while playing and did the game support intrinsic motivation for further investigating how to achieve the goal of the game?

The online survey (see Appendix G) contained various questions, which allow addressing the questions above. We made use of a short version of the intrinsic motivation inventory (IMI) concept (see Appendix H) developed by Wilde et al. (2009). The aim was to evaluate the perception of the game regarding the intrinsic motivation. This is important to assess the players' point of view for further enhancements.

In order to assess the impact of certain learning situations, enjoyment was also measured. This is an important cofactor in the theory of intrinsic motivation.

We received feedback from 30 players (age 21-54), who have completed the online survey after playing an average of 3.5 games. About 70 players played the game without answering the survey. In total, 352 plays were evaluated. Since one successful play lasts ten rounds, we evaluated in how many rounds people either gave up or lost the game, based on the log-files. More than half of the plays ended successfully after the 10th round. Rounds 4 and 5 seem to be crucial for players to continue playing or losing interest. From the plays that ended prematurely, more people chose to quit the game rather than losing according to the rules. We suspect that people tried different strategies to test the game environment rather than finding out how many points these strategies would bring. The early terminations might also explain the low response rate of the questionnaire, since the survey was presented after a finished game in the last round, which, on the other hand, guaranteed that the feedback given by the survey did not base on short-term experiences with the game.

Based on the survey feedback, we assessed how respondents experienced their motivation during the game (see Appendix H). There is a clear indication, that most players enjoyed playing the game with an average of 3.5 for the category enjoyment, see Figure 5.5. However, it should be taken into consideration that positively motivated players might be overrepresented in the survey, as successful players might be more willing to complete a questionnaire after the game.

In contrast, perceptions of the freedom of choice, or “autonomy”, varied significantly among players, which show that there is a high variability in understanding and revealing the underlying mechanisms of the game. Some players felt satisfied with their understanding achieved during the game, some people didn’t. A higher number of participants might reduce uncertainty. We suspect that this feedback is mostly due to the high diversity of participants from various fields (from science of interested public and schools). Some players mentioned insufficient or indistinct explanations of the investment consequences as a reason for underachievement.

The categories “competence” and “relatedness” received an average response (2.5) with a lower variation. This is an indifferent feedback. We suspect that easier access to information on the underlying feedbacks and the mechanism of the game should result in higher values in these categories, which is supported by the results on “autonomy”.

The evaluation of intrinsic motivation is very useful for comparing perceptions of the game and provides various suggestions for further improvements of the prototype, which have been taken up and implemented already in the version that is now online.

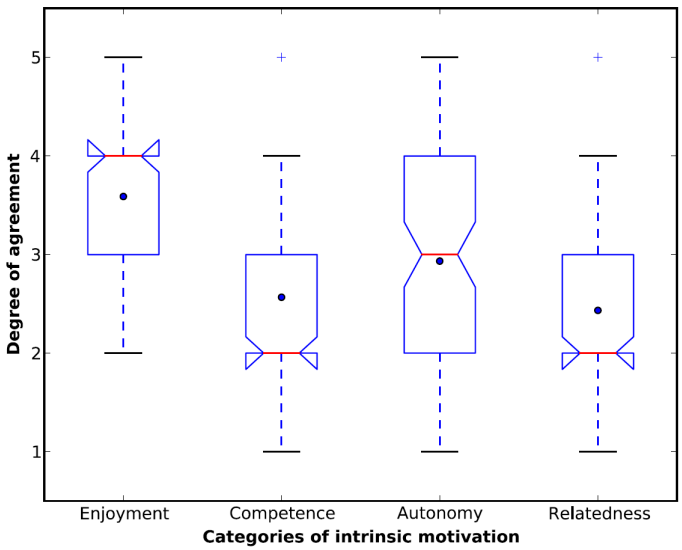

Figure 5.5: The perceived experiences of players (n = 30) during the game. Each category of intrinsic motivation was explored by three questions, where response values ranged from low agreement (1) to high agreement (5). Each box is based on responses of 30 players to 3 questions, resulting in 90 data points. The red line in the boxplots denotes the median; the dot denotes the average value.

5.6 DISCUSSION

5.6.1 *LandYOUs as a base for educational purposes*

Results of the survey suggest that LandYOUs attracts attention and stimulates discussions. The game thus provides a safe and informal environment to arouse players' interest in a complex topic. In LandYOUs, the problems in managing a socio-environmental system are coded sufficiently complex for keeping the player attracted to identify various interactions of a complex land system. On the other hand, complexity is not overwhelming. Players operate in a safe space where the disassociation from error consequences enables low-cost experimentation. This setting supports experiential learning (Barreteau et al., 2007) where knowledge is generated from action, mostly during debriefing (Crookall, 2011), which means here for LandYOUs to discuss consequences of certain investments made and reflect on the "potential realities" (Barreteau et al., 2007) after a game is ended. Role-playing is a typical game trait with which most people are familiar (Garcia-Barrios et al., 2008). This concept enables them to step into a role of another person very easily. Our LandYOUs game supports the action-to-knowledge learning mode described by Crookall (2011). Our findings suggest that the game has a potential to be used for educational purposes, interdisciplinary environmental planning or stakeholder meetings (Voinov et al., 2014).

5.6.2 *Further developments*

Based on the survey feedback, we already implemented some additional features, which make it much easier to reveal interacting mechanisms in the complex land system. Further, we improved the illustration of the score calculator to clarify which aspect sustainability has in land use management. Further improvements can follow three directions: (a) to start the game with more realistic initial conditions, (b) to further develop game functionality and model extensions, and (c) to compile specific educational products, see also Appendix F Section F.8.

1. The initial conditions as well as specific feedbacks can be adapted to situations in the world regions, such as developing countries, countries under high pressure of global change, etc.. This would offer starting conditions, which could qualitatively be closer to real world conditions than the hypothetical world used in the LandYOUs prototype (Vaclavik et al., 2013; Eppink et al., 2012). Various feedbacks would require updates, such as education-consumption relationship, depending on the development of a country or the agricultural production-financial resources relationship, depending of the proportion of the agricultural section of the gross domestic product. This might also require adopting the management options, which might translate differently for various regions. To foster links to real world problems, small informative video links to relevant research projects in various regions of the world on the topic of sustainable land management were added. This keeps up interest after round 5 and also takes up information from the survey (see Section 5.5.2).

2. The game could become even more attractive by implementing specific tasks to be fulfilled by the player, which exemplifies certain processes much clearer (e.g., “Try reducing population growth within 3 rounds”). Second, by the implementation for a multi-player mode, e.g., having multiple players ruling different countries, we are able to mimic global trade of agricultural production. This does not only increase the attraction of the game. Much more important is the fact, that we are able to illustrate in a very convenient and easy way the mechanism how a well-developed country can increase its well-being on the costs of others and vice versa, e.g., implement external effects. This is a very difficult issue to be explained and a computer game like LandYOUs is an ideal platform for illustrating these processes and the unexpected feedbacks.

3. Acknowledging that such a game is just one - but very attractive - element of education, we see the strong need for development of didactic material suited for certain topics in schools and education. We encourage users, especially teachers to develop LandYOUs-specific didactic material using the computer game as a core element with interactive learning effects. LandYOUs already proved being able to stimulate discussions on recent policy related and very applied aspects of land management, such as

- food security (Foley et al., 2011),
- dependency on fossil fuels for agricultural production (as indicated by Figure 5.4, lower left; Seppelt et al. (2014); Eshel et al. (2014),
- dependency of global markets on emerging pattern such as "land grabbing" (Manceur et al., under review),
- influence of single countries activities on the global food markets (Lautenbach et al., 2012), or even
- new definitions of quality of life and human well-being and related indicators beyond GDP (Dasgupta and Ehrlich, 2013).

This includes also online feedback, analysis of tracking data of various players and translation of the learning material in different languages (English, Spanish, Chinese, etc.).

5.7 CONCLUSIONS AND PERSPECTIVES

Besides the quantitative analysis of feedback through the survey of recent users, the application as an educational tool in high schools provides a wide range of qualitative feedback for further development and future applications. So far, we made various experiences with the application in research, high schools and with pupils of different ages. In all practical experiences, we observed that playing the game initiates discussions and quickly introduces various topics of sustainable land management and resource appropriation, such as: effects of consumption pattern on land use change, difference of land use intensity, trade of agricultural products or even education-consumption relationships. This is relevant in classes on geography, mathematics, physics and biology as well as economics. Thus LandYOUs can serve as a core element of interdisciplinary education and teaching. It would be accompanied best by application-specific teaching material for high schools, university but also various kinds of meetings and workshops with stakeholders on land use and environmental issues. Making use of LandYOUs in high school textbooks of various subjects thus can foster interdisciplinary education in environmental science.

Online accessibility using regular web technology and the use of regular web-browsers has shown three major advantages: (1) independence from operating systems, (2) broad availability and easy access (since 1st release LandYOUs is visited 300 times per month) and (3) support of embedding related information to the topic land management, such as related web-pages, video material and other.

In summary, we see LandYOUs as an innovative tool illustrating general characteristics of complex interrelations between landscapes and human well-being. The multi-scale structure allows players to explore specific interactions in a step-wise procedure. This game contributes to bridging the gap between environmental education and landscape modeling science.

Part IV

CONCLUSION

6

DISCUSSION, SYNTHESIS AND OUTLOOK

6.1 SUMMARY OF MAIN RESULTS

6.1.1 *Promoting SRCs for a sustainable bioeconomy*

In Part I of this thesis, we focused on the model-based characterization of opportunities and implications of promoting short rotation coppices (SRCs) in European agricultural landscapes. SRCs resemble a land cover option, which is considered as a synergistic way to meet the increasing wood demand (Mantau et al., 2010; Kaltschmitt, 2011; Bentsen and Felby, 2012) that is on the rise in the face of the politically fostered transition to a sustainable bioeconomy (Hagemann et al., 2016). In contrast to optimistic predictions of the expansion of SRC area (e.g., Helby et al., 2004), the currently existing SRC area in Europe is marginal (Mantau et al., 2010). While various environmental benefits are expected, negative impacts of SRCs have also been identified (Dimitriou et al., 2011). Studies of environmental benefits of SRCs have either been performed at the plot/field scale (e.g., Milner et al., 2015) or conceptually discussed but not tested benefits at the regional scale (e.g., Manning et al., 2015). The impacts of SRC expansion have so far only rarely been investigated in a spatially explicit way at the regional scale (e.g., Fürst et al., 2013). Therefore, we aimed at (1) identifying determinants of SRC expansion, (2) revealing the relative importance of landscape-structural context and economic settings for the expansion and (3) assessing induced regional-scale environmental impacts on biodiversity and multiple ecosystem services (ESS) using modeling. Thereby, we gained insights into the appropriateness of the political promotion of SRCs as option to contribute to a sustainable bioeconomy.

We developed a spatially explicit agent-based model (ABM), which represents the decision-making of profit-maximizing farmers facing the choice between establishing SRCs, cultivating conventional annual crops and abstaining from agricultural activity (fallow land). To gain a comprehensive mechanistic understanding, the expansion of SRCs was modeled and systematically explored in the context of hypothetical stylized landscapes of varying spatial structure. Each landscape was described as regular grid of cells characterized by two layers of spatial distribution for soil quality and transport distances to processing plants. Soil quality represented

the indicator for yield and comprised soil properties such as nutrient content and water holding capacity. Each grid cell in the landscape was aligned to one agent (i.e., farmer), whose decisions were influenced by the site conditions and by the general economic setting such as the market conditions for the different goods. The modeled farmers made specific cultivation decisions, but followed the same principle of profit maximization. Furthermore, they interacted with each other indirectly via an endogenous market. The distributions of soil quality and transport distances in the stylized landscape were generated using a randomization algorithm, which enables to control for the number and the allocation of processing plants as well as the mean and the spatial correlation of the soil quality. We generated ensembles of spatial landscape maps with the same values of these aggregated spatial characteristics, but different explicit spatial configurations (in the following termed "region types"). This approach enabled to test the relevance of (1) the explicit spatial configuration and (2) the aggregated spatial characteristics of the underlying map for the SRC coverage and the pattern of SRC occurrence.

The developed ABM allowed evaluating the relative importance of environmental and economic settings for the SRC cultivation decision, the SRC coverage and the pattern of occurrence (presented in Chapter 2). Model results showed that the willingness to pay for SRC products, the investment expenditures for establishing an SRC plantation and the willingness to pay for the competitive land use form "annual crops" have the strongest influence on the SRC coverage in the landscape. This is in line with empirical studies (e.g., Mola-Yudego and Gonzalez-Olabarria, 2010; Mola-Yudego et al., 2014) as well as with the few existing modeling studies (e.g., Alexander et al., 2014) on SRC expansion. Furthermore, the model results indicated a combined effect of the two site conditions "soil quality" and "transport distance" on the SRC cultivation decision: higher soil qualities compensate for higher distances and, vice versa, lower distances for lower soil qualities. Thereby, SRCs will in most cases be restricted to sites with low soil quality because on sites with high soil quality annual crops are more profitable than SRCs. However, we showed that the threshold below which SRCs are competitive strongly depends on the willingness to pay for the annual crops. Several studies discussed the advantages of SRCs on low-quality sites (e.g., Skevas et al., 2016; Helby et al., 2004; Aust et al., 2014). Occupying sites that are otherwise not used for annual crop production avoids conflicts with food production (cf. Aust et al., 2014; Fitzherbert et al., 2008; van Dam et al., 2009; Hartman et al., 2011), but reduces the amount of fallow land with potential adverse impacts on biodiversity and the terrestrial carbon stock.

We found that the results concerning SRC coverage and distribution differ between ensembles of landscapes with different degrees of spatial correlation of soil quality as aggregated spatial characteristics. In contrast, we found low variability in the results within ensembles of landscapes of the same degree of spatial correlation but different explicit spatial configurations. We hypothesize that the low importance of explicit spatial configuration is caused by the fact that all low-quality areas can be reached, that is, the transport from these to the processing plants is affordable.

This was supported by further model analyses that we conducted, which showed that with a substantial increase in transport price, the variability over the ensemble increases. Overall, this showed that results are transferable between regions of the same type (i.e., which coincide in the degree of spatial correlation), but not between region types, provided transport costs are moderate. This supports Huber et al. (2013) who promote regional-specific policy instruments, which exploit the potential of regions by taking their specific characteristics into account.

In Chapter 3, we examined regional-scale environmental impacts of SRC expansion to evaluate the appropriateness of SRCs as a way to advance a sustainable bioeconomy. Therefore, we applied the model to a specific case study - the Mulde watershed in Central Germany. For this regional context, we evaluated the impact of SRC expansion on biodiversity and multiple ESS, namely crop yields, carbon storage, nutrient and sediment retention, by using the environmental assessment models InVEST and GLOBIO. We covered these locally/regionally occurring ESS as they are seldom included in common environmental assessments of bioenergy feedstock production, e.g., lifecycle assessments focusing on large-scale or global effects such as greenhouse gas emissions (Meyer and Priess, 2014; Koellner and Geyer, 2013). Overall, we found the beneficial impact of SRCs on multiple ESS and biodiversity as discussed in several studies (e.g., Manning et al., 2015; Holland et al., 2015) to be rather low for the individual SRC plot and the regional scale. Only a substantial increase in SRC cultivation area, beyond the regional demand of currently existing combined heat and power plants, will have a positive effect on biodiversity and on single regulating ecosystem services in the specific study region. It is important to note, however, that the same substantial increase will negatively affect food production.

In addition to the regionally aggregated ESS values, we used cluster analysis to identify ESS bundles, i.e., sets of services that appear together repeatedly (Raudsepp-Hearne et al., 2010, p. 5242). We then applied a binomial logistic regression model to assess the factors that distinguish the occurrence of different bundles. We found that the number of sites with balanced ESS supply, i.e., sites on which all considered ESS show similar positive values, is not associated with higher shares of SRCs in the landscape. We showed that these sites with balanced ESS supply can be better explained by biophysical site conditions.

In summary, the regional-scale benefits detected for the specific case study of the Mulde watershed showed to be lower than previously expected. A substantial increase in SRC cultivation area is needed to achieve the predicted environmental benefits of an SRC expansion on ESS and biodiversity.

Finally, we took the insights from the two modeling studies (Chapter 2 and 3) as the starting point to discuss the design of effective policy options to promote SRCs. First, we concluded that investment subsidies combined with environmental minimum requirements (e.g., consideration of displaced land use forms, biophysical site conditions of SRC cultivation locations) are most promising to promote SRC expansion. In general, the effectiveness of an intervention increases with increasing

specificity (ranging from instruments directed at renewable energy in general over wood in general to SRC-specific instruments such as investment subsidies), but so does the risk of inefficiency and market distortions. The risk of market distortions should be kept in mind to avoid unintended negative effects as was seen for the "NaWaRo bonus" (renewable raw material bonus) in earlier versions of the German Renewable Energies Act (EEG) (cf. Britz and Delzeit, 2013). Second, our approach enabled to reflect on a further specific instrument of the current policy of the European Union. Under the reformed Common Agricultural Policy (CAP, 2014-2020), farmers receiving subsidy payments are obliged to reserve at least 5% of their arable land for ecological focus areas (EFAs) and SRCs are regarded as EFAs due to their expected beneficial impacts on the environment (Pe'er et al., 2014). Our results revealed that the rules regarding the EFAs properties need to be specified depending on the environmental goal. They should incorporate biophysical site conditions as a requirement because a policy combining biophysical factors and land use types might more strongly enhance ESS supply.

6.1.2 *Governmental supplementary feeding programs in drylands*

In Part II of this thesis, we evaluated the cost-efficiency performance of governmental supplementary feeding programs in pastoral systems in drylands. Such programs are usually introduced by governments in response to multiple societal challenges related to climate risks, such as poverty alleviation or the maintenance of resilient pastures, or as part of development projects (cf. the Project of Pastoral Development and Livestock in the Oriental PDPEO in Morocco, Mahdi (2007)). Subsidized supplementary feeding is implemented in many pastoral regions in drylands, for instance in North Africa and West Asia (Hazell, 2000). This practice, however, is strongly debated as enabling the maintenance of high livestock numbers during droughts may lead to an increased grazing pressure and an accompanied higher risk of degradation afterwards. In this thesis, we investigated whether the design of supplementary feeding (e.g., timing of supplementation) might mitigate such negative side effects. We evaluated the cost-efficiency performance of governmental supplementation programs in meeting challenges such as the mitigation of climate-induced income risks to pastoralists and the maintenance of resilient pastures.

We developed a process-based ecological-economic rangeland model that describes the feedback between the stocking decisions of a single pastoralist, which are strongly influenced by the access to subsidized fodder provided by the government, and the vegetation dynamics of the pasture. We assumed that the farmer adapts his/her herd size to the available fodder, but tries to keep as many livestock as possible. This corresponds to insights from studies on pastoral systems in Africa, which showed that keeping large herds is used as an insurance against environmental shocks (Lybbert et al., 2004; Robinson and Berkes, 2010). The available fodder is thereby determined by the pasture's state and the granted amount of fodder by

the government. We systematically quantified the performance of 21 supplementation strategies that differ in terms of the way supplements are used (i.e., for pasture regeneration or for maintenance of livestock) as well as the timing, frequency and intensity of supplementation. We used the case without supplementation as reference and assessed the robustness of the findings to various regional contexts. For the latter aspect, we varied biophysical characteristics of the pasture (i.e., capability to build up biomass reserves) and population-dynamic characteristics of the livestock (i.e., fecundity).

Our results revealed negative side effects of the currently applied supplementation strategies such as degradation of pastures or explosion of fodder costs. Maintaining the livestock number at high levels by supplementation, especially during dry seasons, decouples vegetation-livestock dynamics and leads to rangeland degradation (cf. Vetter et al., 2005; Diaz-Solis et al., 2006). We showed that a novel risk-coping strategy that incorporates resting of pastures after droughts supports farmers in coping with climate-induced income risks and is also ecologically as well as economically sustainable. This is in line with other studies that showed the importance of resting (Müller et al., 2007; Quaas et al., 2007). Furthermore, our results suggested that choosing the appropriate amount of granted supplementary fodder is crucial and that the performance of novel supplementation strategies also depends on the regional context (here: the capability to build up biomass reserves as a key mechanism for regeneration and population-dynamic characteristics of the livestock such as fecundity). In summary, we recommend that if governments grant supplementation, resting of the pasture after droughts should be incorporated.

In our study, both the perspective of the pastoralist (i.e., long-term income and income risk) and the perspective of the government (i.e., net economic benefit of subsidy programs) were considered. This two-perspective design enabled us to reveal the importance of considering individual as well as collective benefits. We identified two principle ways of reducing climate-induced income risks of the individual pastoralist: (1) providing subsidized fodder in drought to avoid destocking and after drought to rest the pasture and (2) providing subsidized fodder always when needed. In the latter case, the income risk is reduced through frequent supplements. This is realized at the cost of the government and society because the individual households do not bear the cost of supplementation. In contrast to this, supplementary feeding in drought and post-drought partly invests in maintaining the reserve biomass and thereby the resilience of the pasture. In this case, the intended stabilization of the pastoralist's herd size and income can be achieved from the enhanced puffer capacity of the pasture (cf. Müller et al., 2007; Quaas et al., 2007) that saves future societal monetary resources. In consequence, the individual income risk is mitigated instead of just being shifted to another societal group.

In another study, Müller et al. (2015) analyzed the performance of supplementation strategies that have to be privately financed by the pastoral households. Although the two studies differ with regard to the assumed mechanisms of financing, they come to similar conclusions. In Müller et al. (2015), low costs are of high

importance for the pastoralists and a long-term thinking farmer selects supplementation strategies which strengthen the resilience of the pasture so that his/her herd size and income are stabilized in a natural way. In the case of government financing, as assumed in this thesis, the cost-efficiency requirement leads to an advantage of strategies which improve the resilience of the pasture as natural capital.

Similarly to Part I of this thesis, in Part II, we concluded that governmental supplementary feeding programs should be regionalized and adapted to the ecological characteristics of the rangeland utilization system. Yet, the practicability of such approaches might not be given under current political boundary conditions (Brondizio et al., 2009). Still, evidence from results presented in this thesis should stimulate the discussion on the feasibility of regional-specific policy instruments with stakeholders and policymakers in the specific cases.

6.1.3 *Bridging the gap between land use modeling and environmental education*

In the first two parts of this thesis, we evaluated policy options that aim to promote certain agricultural management strategies, which are believed to be promising for the response to multiple societal challenges. The crucial step in this context was the modeling of individual land use decisions. Besides such transformative policies as a driver, human consumption and behavior strongly influences dietary and material demand patterns and thereby land use. Human behavior strongly depends on the peoples' state of knowledge. Raising public awareness of environmental issues is therefore one way to advance sustainable land management. In addition, integration of stakeholders is discussed as a valuable approach to manage land sustainably (Rounsevell et al., 2012; Voinov and Bousquet, 2010) because it can improve environmental decision processes (Reed, 2008). Moreover, this is increasingly relevant given the decreasing influence of the state on societal development, while the importance of civil society is growing (participation instead of command and control). Therefore, tools for communicating issues of sustainable land management to the interested public and stakeholders are needed. Serious games resemble an innovative approach for environmental education and communication, which gains more and more attention (Barreteau et al., 2007).

A major strength of games is that they can help to communicate complex environmental issues in a simple and engaging manner. Eisenack (2012, p. 3) names the "positive connotation" associated with the gaming experience as a reason for the success of games in achieving an educational purpose. Players operate in a safe virtual space where the disassociation from error consequences enables low-cost experimentation. This setting supports experiential learning where knowledge is generated from action (Barreteau et al., 2007). Experimentation is seen as a crucial mechanism in the context of transformation processes for global sustainability (Chapin et al., 2010).

In Part III of this thesis, we developed the environmental education game LandYOUs. This game allows the player to step into the role of a politician governing a virtual country by the means of different policies. By these policies, the player determines the land use and subsequently a set of interdependent indicators such as human well-being, environmental quality and financial resources. The player is challenged to balance contrasting dimensions of sustainability (economy, environment and social conditions). For example, by investing in afforestation policies the player can increase the forest area in the landscape and therewith the environmental quality. But at the same time, afforestation will generate less financial capital than investing in agricultural production. Subsequently, reduced financial resources will lead to decreased human well-being because people feel insecure, and to reduced investment options in the next round of the game. The model underlying LandYOUs is implemented as a time-discrete system dynamics model which is complemented by a spatially explicit landscape. This game design allowed visualization of spatially explicit land use changes and the incorporation of complex system dynamics. Thereby, it is particularly suitable in the field of land management.

The representation of the enormous number of feedbacks inherent in transformative land use systems, such as the example provided in the previous paragraph, posed a challenge on the game development and implementation. Relevant policies, land use change processes and dynamics of resources and indicators as well as the interrelations between all these components needed to be operationalized in a first step. Thereby, it was important to reduce the complexity of sustainable land management to an appropriate level to attract players' motivation without overwhelming them. In a second step, the identified processes needed to be harmonized with the existing GISCAME framework (Fürst et al., 2010a,b, 2013) and implemented. Finally, the game design needed to be attractive for all user groups. The realization of all these steps was only possible by integrating the knowledge of an interdisciplinary research team of land use modelers, software engineers, economists, graphic designers and environmental didacts.

In Chapter 5, we presented the design, implementation details and gathered experiences from applying LandYOUs. We assessed and highlighted the potential of LandYOUs and concluded that it is a valuable tool for environmental education. This has been shown in different application contexts such as class rooms or public events where LandYOUs initiated discussions on various topics of sustainable land management (e.g., food security or new definitions of human well-being). Moreover, the performance of LandYOUs was evaluated by means of a survey, which revealed that players had on average a lot of fun playing the game, while the degree of understanding was lower and also varied significantly between users. These insights helped to improve the game by providing more information on the underlying processes such as more detailed explanations of indicators' relationships or a graphical explanation of the score calculation. Furthermore, we found that debriefing by a game master or informed person is often valuable to clarify open questions about the topics and feedbacks presented in the game. This is in line with Crookall (2011)

who states the importance of debriefing for the advancement of simulation/gaming as a discipline. In the case of LandYOUs, debriefing includes to discuss the consequences of certain investments made and to reflect on "the relation to the real world" (Barreteau et al., 2007, p. 187).

Overall, LandYOUs is an innovative tool to communicate the complexity of sustainable land management, to initiate discussions and to raise public awareness on the effects of consumption patterns on land use change. Being based on a time-discrete system dynamics model that is complemented by a spatially explicit landscape model, LandYOUs bridges the gap between landscape modeling and environmental education and communication.

6.2 REFLECTIONS ON METHODOLOGICAL APPROACHES

6.2.1 *Value of stylized land use models at the individual scale*

In this thesis, we applied dynamic process-based social-ecological (partly agent-based) models at the individual scale to assess novel policy options in agricultural systems. These models are known to be strong tools to explore and understand causal relationships between drivers and impacts of land use and land cover change as they enable to explicitly model individual actors' decisions with regard to the use of natural resources (for ABMs see Parker et al. (2003); Matthews et al. (2007); Rounsevell et al. (2014)). Within this class of models, we opted for stylized model designs because they sufficiently depict the main features of the system under study, but are simple enough to enable a thorough system understanding (Schlüter et al., 2013). This enabled us to rapidly generate and test hypotheses (Turner, 2003) and to explore new strategies and development pathways (Schlüter et al., 2013).

In particular, we developed the models to assess novel policy options in two different agricultural contexts: promoting SRCs in European agricultural landscapes for supporting a sustainable bioeconomy and governmental supplementary feeding programs to cope with climate risks in pastoral systems in drylands. We used stylized landscapes to derive general insights and system understanding (Chapter 2 and 4) and complemented this by applying the ABM on SRC expansion also to the real landscape of the Mulde watershed in Central Germany (Chapter 3). The two investigated policy contexts showed similarities but also several conceptual differences, which are presented in Table 6.1. The table categorizes these main differences with regard to the societal challenges that led to the emergence of novel policy options, the representation of the actors, their decision-making, the representation of the environment and the evaluation of the outcome of the model. Thereby, we demonstrate a wide range of applications for which process-based models at the individual scale can be useful.

While stylized models come with multiple advantages, there are also challenges or disadvantages compared to structurally more realistic models. Stylized models are

Table 6.1: Differences of the two investigated political contexts.

	Promoting SRCs	**Supplementary feeding programs**
Societal goals	Climate change mitigation through transition to bioeconomy; maintenance of biodiversity and various ESS	Climate change adaptation; poverty alleviation; maintenance of resilient pastures
Actors	Multi-actor perspective	Single-actor perspective
Decisions	Annual and perennial cultivation decisions	Annual stocking decisions
Environment - Space	Spatially explicit	Spatially implicit
Environment - Time	Temporally constant environmental conditions	Temporally stochastic environmental conditions
Evaluation criteria	Supply with SRC and annual crops; coverage with fallow land; biodiversity; various ESS	Long-term income and income risks; herd size; pasture resilience; cost-efficiency

not developed to make quantitative predictions for specific case studies, but rather to reveal qualitative trends for a broader class of situations. This makes quantitative model validation infeasible and the validation of models can only be performed using qualitative patterns (Grimm et al., 2005; Jakoby et al., 2014). A further approach is to replace single model components by a more realistic representation and to assess the robustness of model results. In this thesis, we have done this for evaluating the appropriateness of our landscape generator. The outcome of this analysis is described in Section 6.2.3 below.

6.2.2 *Transferring model results between regions*

A worldwide coverage with case studies assessing the appropriateness of novel policy options in agricultural systems is not feasible. Thus, ways to transfer results between world regions are desirable (Meyer et al., 2015). Stylized models, especially context-specific models that are not based on a specific case study, represent a strong tool in this regard. A context-specific model "is not based on geographic data but model processes are based on data or expert knowledge specific to a case study" (Groeneveld et al., under review). These models are valuable to derive insights beyond a specific case study (Dibble, 2006) and additionally enable to vary the re-

gional biophysical characteristics (such as vegetation growth or landscape structure) and compare the impacts of drivers between region types.

In the two modeling applications presented in Part I and II of this thesis, we performed different approaches of transferability analysis in which we tested key features of the regional environmental system. They enabled to check whether and in what respect policy impacts actually differ substantially between regional contexts and to identify what regional factors steer the impact. Both studies supported the hypothesis that social and environmental impacts of policy options that promote novel management strategies differ between region types. In the following paragraphs, links and differences between the two analyses are described in more detail.

In the study on governmental supplementation programs (Chapter 4), the vegetation was modeled as aggregated measure for one pasture following difference equations describing the vegetation dynamics. For the transferability analysis in this study, we varied parameters describing biophysical characteristics of the pasture and population-dynamic characteristics of the livestock and compared the performance of supplementary feeding programs across region types.

In the studies on the political promotion of SRCs (Chapter 2 and 3), we modeled SRC expansion in a spatially explicit way. In Chapter 2, the analysis was not based on a geographical case study and used a landscape generator to depict spatial characteristics of the underlying map instead. Here, we employed a randomization algorithm to create maps of soil quality with a predefined spatial correlation. We generated ensembles of maps that differ in their explicit spatial realization, but have the same aggregated spatial characteristics. This then also enabled to test the importance of (1) explicit spatial configuration and (2) aggregated spatial characteristics of the underlying map (see Figure 6.1). Investigating the relevance of explicit spatial configuration by quantifying the variation in model predictions due to variation in spatial structure was proposed as spatial uncertainty analysis by Jager et al. (2005). Additionally assessing the impact of aggregated spatial characteristics such as statistical spatial indicators (e.g., spatial correlation) or metrics allowed to test the transferability between region types. In combination with the mechanistic understanding derived from the stylized model, these spatial uncertainty analyses and the classification based on aggregated spatial characteristics enable a mechanistic approach to transferability analyses. Thereby, the classification by means of aggregated spatial characteristics allows a simplification in the sense of a reduction in data requirements. The derived causal understanding on the impacts of landscape-structural characteristics can support the development of spatial indicators for grouping regions of similar policy impacts. These can then be integrated in further landscape analyses.

The main difference between the two approaches of transferability analysis resulted from the representation of the landscape, i.e., spatially explicit vs. implicit representation. The spatially explicit approach is clearly more expensive in terms of implementation, but allows spatial uncertainty analyses and the consideration of spatial drivers. The choice between the two approaches depends on the study con-

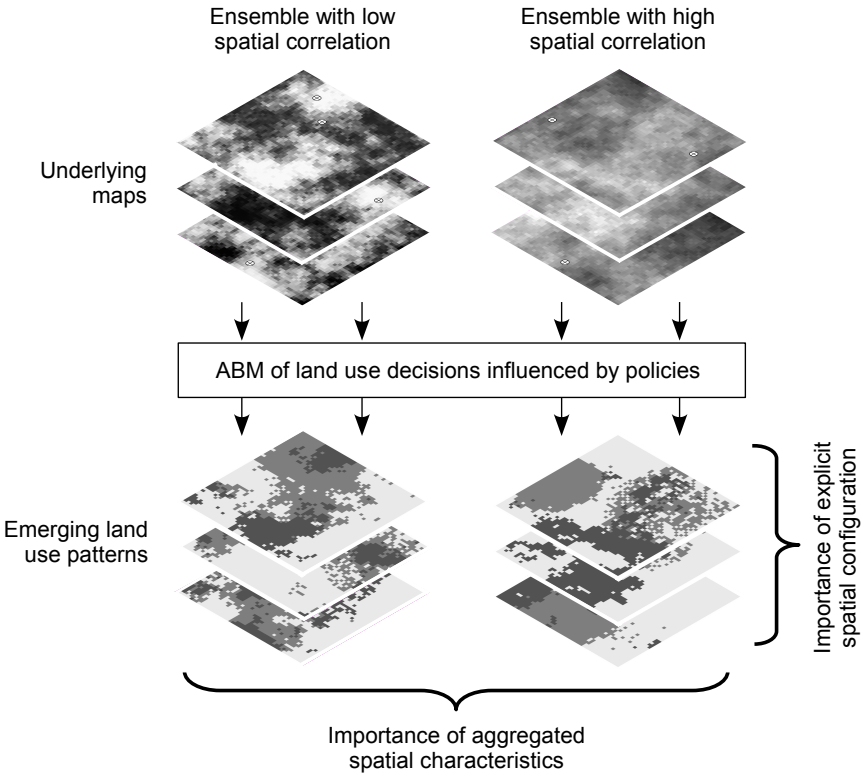

Figure 6.1: Approach to test the importance of the explicit spatial configuration and the aggregated spatial characteristics of the underlying maps.

text. In the supplementary feeding study, the focus was on the temporal long-term effects of pasture dynamics. These can be appropriately represented in a spatially implicit way. For SRC expansion, we were interested in regional-scale landscape-structural effects, which required a spatially explicit assessment. While showing these substantial differences, both studies had in common that crucial biophysical characteristics of the environmental system were identified and varied. Overall, these two examples showed the potential of stylized landscapes for assessing the transferability of model results between region types.

6.2.3 *Insights from applying the stylized model to a case study*

In Chapter 3, we did not investigate a stylized landscape, but applied the ABM to the real landscape of the Mulde watershed in Central Germany as a specific case study. This (i) allowed to explicitly test the appropriateness of the stylized landscape and (ii) broaden the range of performed environmental assessments.

(i) The landscape generator was used to reproduce spatial characteristics of a specific case study. The question is to which extent the landscape generator suffices as “simplified testbed” for analyzing the spatial effects of real landscapes.

We analyzed the appropriateness of the generated stylized landscape within our study on the Mulde watershed. This was done by comparing two methodological approaches: (1) a straightforward approach where we directly run the ABM in the Mulde watershed by using geographic, spatial data as model input (called "direct") and (2) a three-step approach by performing an intermediate step based on the stylized maps ("three-step"). For the latter approach, we first generated the stylized maps representing the distribution of soil qualities (i.e., frequency distribution and spatial correlation) and density of combined heat and power (CHP) plants given in the Mulde. The ABM ran on these stylized maps and generated land use patterns for the investigated land use options (i.e., SRCs, annual crops and fallow land). In the second step, the location of a specific land use option was then related to the site conditions at this location in the underlying map. In our case, we quantified probabilities of SRCs' presence in dependence on soil quality and distance to CHP plants. In the third step, based on these probabilities and the soil quality and CHP plants data, we randomly allocated the SRCs in the Mulde watershed. We then modeled and compared ESS supply for the two landscapes derived with the approaches "direct" and "three-step". We found the results for crop yields, carbon storage, nutrient and sediment retention and biodiversity to be equivalent and therefore concluded that, for the performed ESS assessment, our stylized model is appropriate with regard to the representation of the underlying map.

(ii) The model design of using real vs. stylized landscapes also has implications for the kind of environmental assessment that can be performed. A quantitative ESS assessment (such as sediment export or carbon storage) is only possible in real landscapes. Applying the ABM on SRC expansion to the real landscape of the Mulde watershed enabled to quantify regional-scale biodiversity and ESS supply. In contrast, stylized models combined with landscape generators allow to investigate regions for which aggregated spatial characteristics are sufficient and known, but not the explicit spatial configuration. Furthermore, stylized modeling approaches allow to derive mechanistic understanding on environmental impacts. For example, this allowed to evaluate the effect of supplementation strategies on pasture condition in different region types.

6.3 FUTURE PERSPECTIVES AND CONCLUSION

One of the greatest challenges of the 21st century is meeting the resource demands of mankind while reducing environmental damage caused by land use change (Foley et al., 2011). Furthermore, the need for climate adaptation and mitigation impose challenges on land systems worldwide. This thesis contributed to organize the transformation towards a sustainable development of land systems in two ways. First, we aimed at assessing policy options that promote novel management strategies in two different transformative agricultural contexts using social-ecological modeling (pre-

sented in Chapter 2-4). Second, we aimed at developing and evaluating innovative tools to communicate aspects of sustainable land management to stakeholders and the wider public (Chapter 5).

The potential benefits of the presented methods were only shown for a limited number of examples in this thesis. These methods, which are general, can be applied to further case studies (beyond the Mulde watershed) and also within other contexts in follow-up studies. For example, the ABM used for the evaluation of SRC expansion could also be used for cash crops. Furthermore, the rangeland model that was used for the assessment of supplementary feeding programs could also focus on mobility strategies (i.e., the movement of pastoralists). Additionally, further policy options in agricultural systems such as taxes, subsidies or restriction areas can be included in both of these models.

Another future perspective concerns the representation of human decision-making in process-based models designed at the individual scale (e.g., agent-based models). In the two models presented in this thesis, the decision-making process was kept simple to be close to established theory and could be enhanced in future studies to depict human-decision making in more complex ways. It would be interesting to analyze how this would influence model results. Here, it is an open research question how decision theories beyond rational profit maximization can be operationalized and implemented in process-based models (Schlüter et al., 2012).

Im summary, we derived insights into two novel policy options: promoting SRCs in European agricultural landscapes for a sustainable bioeconomy and governmental supplementary feeding programs to cope with climate risks in drylands. We analyzed these policy options, using social-ecological modeling, with regard to their appropriateness in meeting the multiple societal challenges that led to their emergence in the first place. Methodologically, we contributed to the understanding of how to model and evaluate politically triggered land use changes at the regional scale by using process-based models at the individual scale. In addition, we presented the serious game LandYOUs, which illustrates how simulation modeling can be used within communication strategies. Altogether, in this thesis we developed social-ecological modeling approaches, performed specific policy impact analyses in two transformative agricultural systems using these models and provided a model-based communication tool for environmental education. Thereby, this thesis contributed to model-based decision support for steering transformation towards the sustainable development of land systems.

A

APPENDIX OF CHAPTER 2

This appendix lists the model parameters of the agent-based model on SRC expansion that is used in Chapter 2 of this thesis. A revised version of it is listed as supplementary material for the publication: Schulze, J., Gawel, E., Nolzen, H., Weise, H., Frank, K. (2016). The expansion of short rotation coppices: characterisation of determinants with an agent-based land use model. *GCB Bioenergy*. doi: 10.1111/gcbb.12400.

Table A.1: Model parameters, their values and, if available, the references for parameterization.

Parameter	**Symbol**	**Value**	**Unit**	**Reference**
Technical parameters				
Number of agents	n	2500	-	-
Number of time steps		50	years	-
Agent				
Discount rate	s	6%	-	Average value of discount rates used in SRC studies included in review by Kasmioui and Ceulemans (2012)
Field size	f	≈45	ha	According to mean field sizes in East Germany Fischer et al. (2011)
Landscape				
Mean soil quality		0.5	-	-
Correlation length		0.1	-	Chosen based on visual comparison of maps by Roßberg et al. (2007)
Number of woody biomass processing plants		2.0	-	Chosen based on total expansion of landscape and approximate number per area based on Das et al. (2012)

Annual cultivation				
Aggregated willingness to pay for annual crops	D_{ANN}	6000	money units	-
Production costs	c_{ANN}	2.4	money units	LWK (2014)
Short rotation coppices				
Rotation cycle	a	4.0	years	Aylott et al. (2008); Hillier et al. (2009)
Lifetime	T	20	years	Maximal number of years to not count as forest (BWldG, 2010)
Aggregated willingness to pay for SRC products	D_{SRC}	4000	money units	-
Investment expenditures	v	4.7	money units	Schweinle and Franke (2010); Wagner et al. (2012)
Recovery costs	r	3.6	money units	Schweinle and Franke (2010); Wagner et al. (2012)
Harvest costs	h	1.6	money units	Schweinle and Franke (2010); Wagner et al. (2012)
Fixed transportation costs	τ	0.78	money units	Linear regression based on values from Kröber et al. (2010); Strohm et al. (2012); Wagner et al. (2012); Aust et al. (2014) and the chosen standard rotation length a of 4 years
Transportation price per distance	γ	0.04	money units per km	Linear regression based on values from Kröber et al. (2010); Strohm et al. (2012); Wagner et al. (2012); Aust et al. (2014) and the chosen standard rotation length a of 4 years
Minimal harvest of SRC	h_{min}	0.8	-	

B

APPENDIX 1 OF CHAPTER 3

This appendix contains the full description of the spatially explicit economic simulation model that is used in Chapter 3 of this thesis. It is listed as supplementary material for the publication: Schulze, J., Frank, K., Priess, J.A., Meyer, M.A. (2016). Assessing regional-scale impacts of short rotation coppices on ecosystem services by modeling land-use decisions. Plos One 11(4), e0153862.

The model is an extended version of the model described in Weise (2014). Here, the model description follows the ODD+D protocol (Müller et al., 2013). As an extension of the widely used ODD protocol (Grimm et al., 2006, 2010), the ODD+D protocol puts particular focus on the presentation of human decision-making.

B.1 PURPOSE

The model has been developed to understand the determinants and impacts of the expansion of short rotation coppices (SRCs). The aim of the presented study was to apply the model to the Mulde watershed in Central Germany and to analyse impacts of SRCs on multiple ecosystem services (ESS) and biodiversity.

B.2 ENTITIES, STATE VARIABLES AND SCALES

The model contains following entities: individual land users (from here on called agents), the landscape, grids cells as spatial units and economic markets of different agricultural products as institutions. Table B.1 gives an overview on model entities and associated parameters and state variables.

Exogenous drivers of land use decisions, which are not influenced by processes during a model run, are: soil qualities, demands, number and location of combined heat and power (CHP) plants. Space is explicitly considered in the model. Each cell is occupied by one agent who stays in that cell for the whole simulation and decides in each time step on the land use type in that cell. One time step represents one year and simulations were run for 50 years.

Table B.1: Entities, parameters and state variables of the model.

Entity	Parameters	State variables
Agent	Coordinates	Profit
	Discount rate	
Landscape	Size	Shares of land use types
Grid cell	Coordinates	Land use
	Soil quality	
	Distance to CHP plants	
Market for annual agricultural crops	Demand	Price Supply
Market for SRC	Demand	Price Supply

B.3 PROCESS OVERVIEW AND SCHEDULING

Here, the processes of the model are briefly specified to allow a general overview of the model and its dynamics. For a detailed description of the processes see Section B.8.

Process 1: Initialization of landscape. Before the start of the simulation, the landscape is initialized based on empirical spatial data, i.e., distribution of soil quality and spatial allocation of CHP plants.

Process 2: Decision-making of agents. In each time step all agents decide sequentially in a random order between three different land use types: no cultivation, annual agricultural crops for food or feed production and SRCs.

Process 3: Calculation of regional supply and market prices. After each agent decision, the market prices for the different commodities (woody products from SRCs and other agricultural crops from annual cultivation) are updated based on the exogenously given demands and current regional supply.

B.4 DESIGN CONCEPTS

B.4.1 *Theoretical and empirical background*

A main concept is the implementation of markets for the different agricultural commodities (woody products from SRCs and other agricultural crops from annual cultivation). Market prices in the model are determined by the balance of supply and demand. This price formation on the market is in line with standard economic theory (e.g., equilibrium concept; cf. Mankiw and Taylor (2006); Engelkamp and Sell (2007)). At this, market price is determined by an externally given demand and a

supply that is solely generated by the land use decisions of the agents (i.e., endogenous markets). We assume that the market price is equivalent across all CHP plants and is determined by the joint supply from all agents (termed "regional price"). Besides utilizing SRC products, CHP plants are also distributing resources: plants with a high supply (i.e., higher than their own capacity) are able to transport and to sell to another plant or other customers. This means that the agents always supply the closest CHP plant as they receive the same price at each plant and the transport costs are minimal for the closest plant.

However, we tested this scenario against a second scenario in which the market price is formed separately for each of the CHP plants and is determined by the amount of SRC that is sold to this specific plant (termed "local price"). Here, market prices might vary between plants. In the current study, simulated land use patterns and the regional ESS showed to be the equivalent across both price scenarios (see Table C.1 and Table C.2). Therefore, we focus on the "regional price" scenario in this study and will present the details of the "local price" scenario only verbally in the submodels below.

The agents are rational profit maximizers, i.e., agents have clear preferences over all possible land use options and aim at maximizing their income. At this, it is assumed that agents have full information (that are available in the model) and the needed cognitive ability to process all possible options. This decision model was chosen to be close to established theory. Furthermore, we believe that profit maximization is an appropriate assumption for industrial agricultural decisions. To enable the comparison between land use types with different lifespans, the equivalent annual annuity approach (see for example Brigham and Houston (2006)) from investment theory was chosen. This approach is appropriate as it is often recommended to land users interested in SRC practice in Germany (for example Schweinle and Franke (2010)) and has been used in several studies on the financial analysis of SRCs (Kasmioui and Ceulemans, 2012).

B.4.2 *Individual decision-making*

The agents, namely individual farmers, decide between three different land use types: no cultivation, annual crops for food or feed production and SRCs. Agents follow a rational profit maximization approach using an equivalent annual annuity approach (see above). Agents adapt to changing market prices. Neither social norms nor cultural values are incorporated in the model. Spatial aspects are incorporated as the distance to CHP plants influences the decision via resulting transportation costs. Temporal aspects play a role as discounting of future profits is incorporated in the equivalent annual annuity approach. Discount rates are seen as subjective discount rates which can vary depending on personal risk aversion (Barberis and Thaler, 2003).

B.4.3 *Learning*

Learning is not incorporated in the model.

B.4.4 *Individual sensing*

The agent knows its current land use, the location factors of its land, i.e., soil quality and distance to CHP plants, and the current market price. The agents do not perceive information from other agents directly. However, they do sense the current total supply which comprises all agents currently chosen land use type. The sensing process is not modeled explicitly, it is not erroneous and no costs of sensing are incorporated.

B.4.5 *Individual prediction*

Agents are not able to predict changes in market prices. However, they are able to predict how their own decision will impact the current market price.

B.4.6 *Interaction*

Agents interact indirectly via the endogenous market. The land use decision of an agent influences the market prices, which then influences the land use decisions of other agents.

B.4.7 *Collectives*

There are no collectives incorporated in the model.

B.4.8 *Heterogeneity*

Agents are heterogeneous with regard to the location factors of their land. Here, the soil qualities as well as the distances to CHP plants differ between cells. Soil quality influences productivity of annual crops as well as of SRCs. Distances to CHP plants determine transportation costs of SRC products.

B.4.9 *Stochasticity*

Agents make their decisions in a random order.

B.4.10 *Observation*

With the goal of this study to assess impacts of SRC expansion in the Mulde watershed in Central Germany, the number and coordinates of SRCs are observed as main output variables.

B.5 IMPLEMENTATION DETAILS

The model was implemented in C++ using Embarcadero® C++Builder® 2010.

B.6 INITIALIZATION

The model landscape is initialized with spatial data on soil quality (LfULG, 2012) and CHP plants (Das et al., 2012). At the beginning, all cells are not under cultivation.

B.7 INPUT

Spatial data on soil quality (LfULG, 2012), CHP plants (Das et al., 2012) and on current land use (Wochele et al., 2014; Wochele-Marx et al., 2015) is used.

B.8 SUBMODELS

B.8.1 *Initialization of landscape*

Based on the current land use (Wochele et al., 2014; Wochele-Marx et al., 2015), each cropland cell of the Mulde watershed is assigned to one agent. In total, this amounts to 9537 agents/cells. For each cell the soil quality value and the distances to the CHP plants are set based on the spatial data (Das et al., 2012; LfULG, 2012). For the "regional price" scenario, only the distance to the closest CHP plant is needed as the market price is equivalent across all CHP plants (see Section B.4.1); hence, agents always supply the closest CHP plant.

B.8.2 *Decision-making of agents*

The agent chooses between three land use types: SRCs, annual agricultural crops (ANN) or no cultivation (NoC). From these, the agent chooses the option that maximizes its profits. The profit calculation differs between the three land use types. No cultivation yields neither costs nor revenue and its profit for agent i is therefore:

$$P^i_{NoC} = 0 \tag{B.1}$$

For annual agricultural crops the following profit function applies:

$$P^i_{ANN}(t) = p_{ANN}(t) \cdot prod^i_{ANN} - pca \tag{B.2}$$

where $p_{ANN}(t)$ is the current market price (calculated by Equation B.10), $prod^i_{ANN}$ the productivity of annuals crops in the cell of agent i and pca the production costs of annuals. The productivity of annual crops is determined by the location factor soil quality by assuming a linear relationship:

$$prod^i_{ANN} = sq^i \tag{B.3}$$

where sq^i is the soil quality of the cell of agent i. As pointed out by Zhang et al. (2007) soil properties strongly impact the agricultural output. Similarly, we assume that productivity and soil quality are linearly correlated with both factors being normalized between 0 and 1. Thereby, we follow the concept of using soil values ("Bodenwertzahl") to classify German soils (GD NRW, 2014). The soil value is a measure for differences in net yield under proper cultivation that are solely determined by differences in soil (GD NRW, 2014). With Equation B.3, a soil value sq^i of 0.5 represents a reduction in net yield by 50% of the maximal yield (Zhang et al., 2007; Petzold et al., 2014).

As SRCs represent long-term investment decisions, concepts of intertemporal choice should be taken into account in the profit calculation. The underlying idea is that people value profit differently at different points in time. For this study, the equivalent annual annuity approach (for example described in Brigham and Houston (2006)) from investment theory was chosen. This approach is appropriate as it is often recommended to land users interested in SRC practice in Germany (for example Schweinle and Franke (2010)) and has been used in several studies on the financial analysis of SRCs (Kasmioui and Ceulemans, 2012).

In a first step, the profit of agent i in year t $P^i_{SRC}(t)$ over the whole life time of the SRC is calculated by:

$$P^i_{SRC}(t) = \begin{cases} p_{SRC}(t) \cdot prod^i_{SRC} \cdot rot - costs_i(t) & \text{, if } t \mod rot = 0 \\ -costs_i(t) & \text{, else} \end{cases} \tag{B.4}$$

where $p_{SRC}(t)$ is the current market price in year t for SRC products produced in one year on optimal soil conditions calculated by Equation B.10, $prod^i_{SRC}$ the productivity of SRCs in the cell of agent i, rot the number of years after which SRCs are harvested and $costs_i(t)$ are all incurring costs in year t. For the "regional price" scenario, this profit is only calculated for supplying the closest CHP plant because agents receive the same price at each plant and the transport costs are minimal for the closest plant. In contrast, for the "local price" scenario the profit differs between the 15 CHP plants present in the Mulde watershed because market prices $p_{SRC}(t)$ and transportation costs (included in the $costs_i(t)$ calculated by Equation B.6) are different between the 15 plants. These differences are more closely described below.

The productivity of SRCs is given by:

$$prod^i_{SRC} \begin{cases} prod_{min} + 0.2 & \text{, if } sq^i \geq 0.5 \\ prod_{min} & \text{, if } sq^i < 0.5 \end{cases} \tag{B.5}$$

where $prod_{min}$ is the productivity on cells with a soil quality sq^i below 0.5. Hence, the productivity of SRCs is assumed to decrease on poor soils (as was found by Ali (2009)). At this, the dependence on soil quality is less pronounced than for annual crops (see Equation B.3) because studies showed that biomass yield from SRCs is dependent on further factors such as age of plantation or precipitation (Ali, 2009). Nevertheless, in our model the consideration of biophysical location factors is restricted to the soil quality due to simplicity reasons.

Finally, all occurring costs for agent i are calculated by:

$$costs_i = \begin{cases} ic & \text{, if } t = 0 \\ hc + rot \cdot tc^i & \text{, if } t \mod rot = 0 \text{ and } t < T \\ hc + rot \cdot tc^i + rc & \text{, if } t = T \\ 0 & \text{, else} \end{cases} \tag{B.6}$$

where rot is the number years after which SRCs are harvested, ic are the investment costs, hc the harvest costs, tc^i the transportation costs of wood produced per year and rc the recovery costs. In the initial year the investment costs ic are due, at the end of each rotation cycle harvest costs hc as well as transportation costs to the CHP plant tc^i occur and finally at the end of the lifetime additional recovery costs of the land rc have to be paid. The transportation costs are linearly dependent on the distance to CHP plant:

$$tc^i = tc_{min} + tc_{slope} \cdot d^i \cdot prod^i_{SRC} \cdot yield \tag{B.7}$$

where d^i is the distance of agent i to the closest CHP plant and calculated as Euclidean distance (Deza and Deza, 2013) from the data on CHP plants (Das et al., 2012), tc_{min} are fixed costs for transportation, tc_{slope} the transport price per distance, $prod^i_{SRC}$ the productivity of SRCs in the cell of agent i and $yield$ is the yield of SRC products produced in one year on optimal soil conditions. For the "regional price" scenario the distance d^i is the distance to the closest CHP plant. For the "local price" scenario the transport costs to each of the 15 CHP plants in the Mulde watershed need to be calculated by Equation B.7 with d^i being the distance to the specific CHP plant.

From the sequence of profits $P^i_{SRC}(t)$, the net present value is calculated as the sum of the discounted profits:

$$NPV^i = \sum_{t=0}^{LT} (1+r)^{-t} \cdot P^i_{SRC}(t) \tag{B.8}$$

where LT is the lifetime of the plantation, r the discount rate and $P^i_{SRC}(t)$ the profit in year t calculated by Equation B.4.

Subsequently, the equivalent annual value EAV is calculated from the net present value NPV to enable the comparison of land use options with unequal lifespans:

$$EAV^i = \frac{1}{1-(1+r)^{-LT}} \cdot NPV^i \tag{B.9}$$

where r is the discount rate, LT the lifetime of a SRC plantation and NPV^i the net present value calculated by Equation B.8.

In a final step, the agent compares the equivalent annual value EAV^i with the possible profit from annual agricultural production $P^i_{ANN}(t)$ and chooses the option with the higher profit. If both, the equivalent annual value EAV^i of SRC and the profit of annual agricultural crops $P^i_{ANN}(t)$ would yield negative incomes, the agent decides to not cultivate its land in the current year.

B.8.3 *Calculation of regional supply and market prices*

After each decision step, the regional supplies $S_j(t)$ and the market prices $p_j(t)$ for the different products j, i.e., ANN and SRC, are updated by calculating:

$$p_j(t) = \frac{D_j}{S_j(t)} \text{ with } S_j(t) = \sum_{i=1}^{N} h^i_j(t) \tag{B.10}$$

where D_j is the demand for product $j \in \{ANN, SRC\}$, N the number of agents and $h^i_j(t)$ the harvest amount of product j in cell i given by:

$$h_{ANN}(t) = \begin{cases} prod^i_{ANN} & \text{, if land use is } ANN \\ 0 & \text{, if land use is not } ANN \end{cases} \tag{B.11}$$

$$h_{SRC}(t) = \begin{cases} prod^i_{SRC} & \text{, if land use is } SRC \\ 0 & \text{, if land use is not } SRC \end{cases} \tag{B.12}$$

For the "local price" scenario, the market price $p_j(t)$ needs to be calculated separately for each of the 15 CHP plants. In that case the total demand D_{SRC} is equally distributed between the 15 CHP plants and for the supply $S_j(t)$ only that of the specific CHP plant is taken.

B.9 PARAMETER SET

Table B.2 shows the names of all parameters used in the model, their values and, if available, the references for their parameterization.

Table B.2: Parameters of the model.

Parameter	Symbol	Value	Unit	Reference
Technical parameters				
Number of agents	N	9537	-	-
Number of time steps	T	50	years	-
Agent				
Discount rate	r	6%	-	Average value of discount rates used in SRC studies included in a review by Kasmioui and Ceulemans (2012)
Annual crops				
Demand for annual crops	D_{ANN}	31000	money units per year and ha	Chosen based on initial shares of agricultural and fallow land currently present in case study (Wochele et al., 2014; Wochele-Marx et al., 2015; EEA, 2013)
Production costs per ha	pca	2.4	money units per ha	LWK (2014)
SRCs				
Demand for SRC products	D_{SRC}	460	money units per year and ha	Chosen based on current demand in case study (solely given by CHP plants present) (Das et al., 2012)
Investment costs	ic	4.7	money units	Schweinle and Franke (2010); Wagner et al. (2012)
Recovery costs	rc	3.6	money units per ha	Schweinle and Franke (2010); Wagner et al. (2012)

Harvest costs	hc	1.6	money unit per ha	Schweinle and Franke (2010); Wagner et al. (2012)
Rotation cycle	rot	4	years	Aylott et al. (2008); Hillier et al. (2009)
Lifetime	LT	20	years	Maximal number of years to not count as forest (BWldG, 2010)
Minimal productivity	$prod_{min}$	0.8	-	-
Minimal transportation costs	tc_{min}	0.02	money units per dry ton	Linear regression based on values from Kröber et al. (2010); Strohm et al. (2012); Wagner et al. (2012)
Slope transportation costs	tc_{slope}	0.001	money units per dry ton and distance	Linear regression based on values from Kröber et al. (2010); Strohm et al. (2012); Wagner et al. (2012)
Yield	$yield$	12	dry tons per ha	Aust et al. (2014)

C

APPENDIX 2 OF CHAPTER 3

This appendix contains the tables supporting Figure 3.3. It is listed as supplementary material for the publication: Schulze, J., Frank, K., Priess, J.A., Meyer, M.A. (2016). Assessing regional-scale impacts of short rotation coppices on ecosystem services by modeling land-use decisions. Plos One 11(4), e0153862.

Table C.1: Provisioning ESS values for the economic (scenarios 1-4) and the policy-driven scenarios (scenarios 5-6) are indicated compared to the baseline scenario (italics); the upper part shows the regional price scenario and the lower part the local price scenario.

Provisioning ecosystem servives (regional price)	SRC yield [t a^{-1}]	Cereals [t a^{-1}]	Δ baseline scenario	Maize silage [t a^{-1}]	Δ baseline scenario	Rapeseed [t a^{-1}]	Δ baseline scenario
Baseline scenario 2006	*0*	*621 068*		*787 037*		*127 765*	
Scenario 1: standard demand	40 642	599 745	-3%	770 834	-2%	123 221	-4%
Scenario 2: medium demand	108 516	566 016	-9%	729 735	-7%	117 142	-8%
Scenario 3: high demand	434 478	455 928	-27%	543 905	-31%	89 582	-30%
Scenario 4: very high demand	895 168	318 438	-49%	324 691	-59%	34 919	-73%
Scenario 5: EFA (bad soils)	170 108	543 606	-12%	695 843	-12%	111 159	-13%
Scenario 6: EFA (good soils)	403 301	476 539	-23%	663 341	-16%	105 279	-18%

Provisioning ecosystem services (local price)	SRC yield [t a^{-1}]	Cereals [t a^{-1}]	Δ baseline scenario	Maize silage [t a^{-1}]	Δ baseline scenario	Rapeseed [t a^{-1}]	Δ baseline scenario
Baseline scenario (2006)	*0*	*621 068*		*787 037*		*127 765*	
Scenario 1: standard demand	38 154	600 353	-3%	787 037	0%	123 173	-4%
Scenario 2: medium demand	101 075	566 137	-9%	723 570	-8%	116 497	-9%
Scenario 3: high demand	401 901	454 504	-27%	554 516	-30%	89 897	-30%
Scenario 4: very high demand	879 165	318 104	-49%	330 606	-58%	58 804	-54%
Scenario 5: EFA (bad soils)	170 108	543 606	-12%	695 843	-12%	111 159	-13%
Scenario 6: EFA (good soils)	403 301	476 539	-23%	663 341	-16%	105 279	-18%

Table C.2: Regulating ESS values for the economic (scenarios 1-4) and the policy-driven scenarios (scenarios 5-6) are indicated compared to the baseline scenario (italics); the upper part shows the regional price scenario and the lower part the local price scenario.

Regulating ecosystem services (regional price)	C storage [t]	Δ baseline scenario	Sediment export [t a^{-1}]	Δ baseline scenario	P export [kg a^{-1}]	Δ baseline scenario	Biodiversity MSA (mean)	Δ baseline scenario
Baseline scenario (2006)	*37 318 089*		*66 871*		*341 343*		*0.126*	
Scenario 1: standard demand	37 162 382	0%	65 501	-2%	336 435	-1%	0.129	2%
Scenario 2: medium demand	37 531 713	1%	63 390	-5%	331 581	-3%	0.135	7%
Scenario 3: high demand	39 303 362	5%	54 112	-19%	322 843	-5%	0.153	22%
Scenario 4: very high demand	41 143 284	10%	41 664	-38%	311 872	-9%	0.173	38%
Scenario 5: EFA (bad soils)	37 826 181	1%	61 969	-7%	326 501	-4%	0.139	11%
Scenario 6: EFA (good soils)	38 305 760	3%	54 989	-18%	333 165	-2%	0.139	10%

Regulating ecosystem services (local price)	C storage [t]	Δ baseline scenario	Sediment export [t a^{-1}]	Δ baseline scenario	P export [kg a^{-1}]	Δ baseline scenario	Biodiversity MSA (mean)	Δ baseline scenario
Baseline scenario (2006)	*37 318 089*	*66 871*		*341 343*		*0,126*		
Scenario 1: standard demand	37 135 901	0%	65 458	-2%	336 317	-1%	0.127	1%
Scenario 2: medium demand	37 478 812	0%	63 506	-5%	332 131	-3%	0.134	7%
Scenario 3: high demand	39 251 839	5%	54 009	-19%	322 849	-5%	0.153	21%
Scenario 4: very high demand	41 106 851	10%	41 587	-38%	312 123	-9%	0.173	38%
Scenario 5: EFA (bad soils)	37 826 181	1%	61 969	-7%	326 501	-4%	0.139	11%
Scenario 6: EFA (good soils)	38 305 760	3%	54 989	-18%	333 165	-2%	0.139	10%

D

APPENDIX 3 OF CHAPTER 3

This appendix contains the tables listing the set of potential explanatory variables for Table 3.3 and Figure 3.5 and the entire regression results for Figure 3.5. It is listed as supplementary material for the publication: Schulze, J., Frank, K., Priess, J.A., Meyer, M.A. (2016). Assessing regional-scale impacts of short rotation coppices on ecosystem services by modeling land-use decisions. Plos One 11(4), e0153862.

Table D.1: Potential variables to explain ESS cluster differences.

Independent variable	**Unit**	**Methodological reference (data source)**
Landscape composition		Jones et al. (2001)
Share of LU/LC classes in the neighborhood:		EEA (2013); Wochele et al. (2014); Wochele-Marx et al. (2015)
Forest	[%]	
Pasture	[%]	
SRC	[%]	
Cropland	[%]	
Urban	[%]	
Water	[%]	
Distance to stream	[m]	Kissel et al. (2015)
Naturalness		
Urbanity	[score]	EEA (2013); Wochele et al. (2014); Wochele-Marx et al. (2015); Meyer et al. (2015)
Topography		Wrbka et al. (2004)
Elevation	[m]	Lehner et al. (2008)
Slope	[%]	Lehner et al. (2008)
Curvature	[score]	Lehner et al. (2008)
Aspect	[°]	Lehner et al. (2008)
Soil parameters		Qiu and Turner (2013)
Effective rooting depth	[mm]	Panagos et al. (2006); LfULG (2012)
Available water holding capacity	[cm cm^{-1}]	Panagos et al. (2006); LfULG (2012)
Soil quality index ("Ackerzahl")	[score]	LfULG (2012)
Erodibility (K)	[t ha h ha^{-1} MJ^{-1} mm^{-1}]	LfULG (2012); Bischoff (2014)
Climate		
Precipitation	[mm a^{-1}]	Jäckel et al. (2012)
Reference Evapotranspiration (10 arc-min)	[mm a^{-1}]	FAO Geonetwork (2014)
Erosivity (R)	[MJ mm ha^{-1} h^{-1} a^{-1}]	Bräunig (2013)

Table D.2: Factors characterizing ESS cluster 1 and 2 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 1; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 2. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 3262.2, df = 15, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2 = 85.5, df = 3, p <2.2e-16).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	5.1502	0.5214	9.8770	<0.0001	***
Topography and soil parameters					
Elevation [m]	-4.7700	0.6076	-7.8500	<0.0001	***
Slope [%]	3.0140	0.4638	6.4980	<0.0001	***
Aspect [°]	0.2484	0.1725	1.4400	0.1500	
Curvature [score]	-2.9456	0.5438	-5.4170	<0.0001	***
Effective rooting depth [mm]	-3.2246	0.5502	-5.8600	<0.0001	***
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	1.5463	0.5905	2.6190	0.0088	**
Available water holding capacity [cm cm^{-1}]	-1.2713	0.8935	-1.4230	0.1548	
Soil quality index	5.5520	0.5954	9.3240	<0.0001	***
Climate					
Precipitation [mm]	1.4046	0.3846	3.6520	0.0003	***
Reference Evapotranspiration [mm a^{-1}]	-0.6073	0.3212	-1.8910	0.0587	.
Landscape composition					
Forest, 5 km buffer [%]	-3.7710	0.4805	-7.8480	<0.0001	***
Pasture, 5 km buffer [%]	1.1935	0.3157	3.7810	0.0003	***
SRC, 5 km buffer [%]	-7.7616	0.3400	-22.8300	<0.0001	***
Water, 5 km buffer [%]	-0.5853	0.3163	-1.8510	0.0642	.
Distance to stream [m]	-1.0951	0.2177	-5.0300	<0.0001	***

Table D.3: Factors characterizing ESS cluster 1 and 3 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 1; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 3. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 2676.4, df = 15, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2 = 85.5, df = 3, p <2.2e-16).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	12.2106	0.8513	14.3430	<0.0001	***
Topography and soil parameters					
Elevation [m]	-4.5616	0.5515	-8.2710	<0.0001	***
Slope [%]	-4.8060	0.5114	-9.3980	<0.0001	***
Curvature [score]	-4.5616	0.5515	-8.2710	<0.0001	***
Effective rooting depth [mm]	-7.3096	0.6962	-10.4990	<0.0001	***
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	-7.3068	0.7143	-10.2300	<0.0001	***
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	-2.5418	0.5072	-5.0110	<0.0001	***
Available water holding capacity [cm cm^{-1}]	-4.7678	1.2038	-3.9610	<0.0001	***
Soil quality index	9.3495	0.7668	12.1940	<0.0001	***
Climate					
Precipitation [mm]	2.9361	0.4461	6.5820	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	-3.4618	0.4631	-7.4760	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	-6.4389	0.6306	-10.2100	<0.0001	***
Pasture, 5 km buffer [%]	3.2612	0.4199	7.7670	<0.0001	***
SRC, 5 km buffer [%]	-2.5557	0.3863	-6.6160	<0.0001	***
Urban, 5 km buffer [%]	1.2493	0.6562	1.9040	0.0569	.
Water, 5 km buffer [%]	-0.8468	0.3011	-2.8120	0.0049	**
Distance to stream [m]	-1.6530	0.2814	-5.8730	<0.0001	***

Table D.4: Factors characterizing ESS cluster 1 and 4 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 1; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 4. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1885.4, df = 11, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2 = 13.7, df = 3, p = 3.4e-3).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	1.6243	0.3484	4.6620	<0.0001	***
Topography and soil parameters					
Slope [%]	1.2629	0.3618	3.4910	0.0005	***
Aspect [°]	-0.3112	0.1484	-2.0970	0.0360	*
Curvature [score]	-1.2291	0.4226	-2.9090	0.0036	**
Effective rooting depth [mm]	-3.8130	0.4469	-8.5320	<0.0001	***
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	1.0086	0.2800	3.6020	0.0003	***
Soil quality index	4.6556	0.4595	10.1320	<0.0001	***
Climate					
Precipitation [mm]	0.7629	0.2363	3.2290	0.0012	**
Landscape composition					
Forest, 5 km buffer [%]	-1.9671	0.2927	-6.7210	<0.0001	***
SRC, 5 km buffer [%]	-4.111	0.2258	-18.206	<0.0001	***
Water, 5 km buffer [%]	0.7133	0.2316	3.0790	0.0021	**
Distance to stream [m]	-0.4168	0.1734	-2.4040	0.0162	*

Table D.5: Factors characterizing ESS cluster 1 and 5 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 1; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 5. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2= 1445.4, df = 13, p <2.2e-16).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	-6.5830	0.6293	-10.4610	<0.0001	***
Topography and soil parameters					
Elevation [m]	5.3039	0.6956	7.6250	<0.0001	***
Slope [%]	2.9376	0.5522	5.3200	<0.0001	***
Aspect [°]	-0.6175	0.2155	-2.8650	0.0042	**
Curvature [score]	6.1831	0.6694	9.2360	<0.0001	***
Effective rooting depth [mm]	2.2987	0.3414	6.7340	<0.0001	***
Available water holding capacity [cm cm^{-1}]	12.0156	0.9828	12.2260	<0.0001	***
Climate					
Precipitation [mm]	-2.5332	0.4769	-5.3120	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	1.3533	0.3957	3.4200	0.0006	***
Landscape composition					
Forest, 5 km buffer [%]	-0.6897	0.4264	-1.6170	0.1058	
SRC, 5 km buffer [%]	-0.6687	0.2887	-2.3160	0.0206	*
Urban, 5 km buffer [%]	-2.9291	0.3100	-9.4470	<0.0001	***
Water, 5 km buffer [%]	1.9425	0.3846	5.0510	<0.0001	***
Distance to stream [m]	-0.6830	0.2542	-2.6870	0.0072	**

Table D.6: Factors characterizing ESS cluster 1 and 6 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 1; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 6. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2= 1600.2, df = 12, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2= 37.0, df = 3, p = 4.5e-08).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	8.8382	0.5830	15.1590	<0.0001	***
Topography and soil parameters					
Elevation [m]	-3.9391	0.6124	-6.4320	<0.0001	***
Slope [%]	-8.6778	0.4189	-20.7130	<0.0001	***
Curvature [score]	-0.7426	0.4466	-1.6630	0.0963	.
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	1.0074	0.3419	2.9460	0.0032	**
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	-1.6357	0.6790	-2.4090	0.0160	*
Available water holding capacity [cm cm^{-1}]	-2.9583	0.7628	-3.8780	0.0001	***
Climate					
Precipitation [mm]	2.4498	0.3919	6.2510	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	-4.4756	0.3909	-11.4510	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	-3.9054	0.4851	-8.0500	<0.0001	***
Pasture, 5 km buffer [%]	1.5455	0.3502	4.4140	<0.0001	***
SRC, 5 km buffer [%]	-2.1195	0.2992	-7.0840	<0.0001	***
Urban, 5 km buffer [%]	-2.4177	0.3991	-6.0580	<0.0001	***

Table D.7: Factors characterizing ESS cluster 2 and 3 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 2; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 3. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1466.0, df = 14, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2 = 134.0, df = 3, p <2.2e-16).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	4.7764	0.7592	6.2910	<0.0001	***
Topography and soil parameters Elevation [m]	-2.9234	0.7200	-4.0610	<0.0001	***
Slope [%]	-6.8190	0.5473	-12.4600	<0.0001	***
Curvature [score]	-1.3193	0.5751	-2.2940	0.0218	*
Effective rooting depth [mm]	-1.4654	0.6322	-2.3180	0.0204	*
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	-1.8041	0.4970	-3.6300	0.0003	***
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	-5.9939	0.7658	-7.8270	<0.0001	***
Available water holding capacity [cm cm^{-1}]	-1.9397	0.8838	-2.1950	0.001	*
Soil quality index	2.3024	0.6988	3.2950	<0.0001	***
Climate					
Precipitation [mm]	2.9945	0.4360	6.8690	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	-3.8305	0.5029	-7.6180	<0.0001	***
Landscape composition					
Pasture, 5 km buffer [%]	3.4670	0.3238	10.7080	<0.0001	***
SRC, 5 km buffer [%]	6.6071	0.4044	16.3380	<0.0001	***
Water, 5 km buffer [%]	-0.6291	0.3470	-1.8130	0.0699	.
Urban, 5 km buffer [%]	2.8488	0.7024	4.0560	<0.0001	***

Table D.8: Factors characterizing ESS cluster 2 and 4 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 2; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 4. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 609.4, df = 15, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2 = 30.0, df = 3, p = 1.5e-06).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	-0.6899	0.5579	-1.2370	0.2162	
Topography and soil parameters					
Elevation [m]	4.0458	0.5075	7.9730	<0.0001	***
Slope [%]	-2.0923	0.4452	-4.6990	<0.0001	***
Aspect [°]	-0.3247	0.1553	-2.0910	0.0365	*
Curvature [score]	2.2409	0.4753	4.7150	<0.0001	***
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	0.9522	0.3431	2.7760	0.0055	**
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	-1.7973	0.4962	-3.6220	0.0003	***
Soil quality index	-2.0799	0.3625	-5.7370	<0.0001	***
Climate					
Precipitation [mm]	-0.6322	0.3272	-1.9320	0.0533	.
Reference Evapotranspiration [mm a^{-1}]	0.7080	0.3247	2.1810	0.0292	*
Landscape composition					
Pasture, 5 km buffer [%]	-2.2926	0.2347	-9.7700	<0.0001	***
SRC, 5 km buffer [%]	1.7940	0.3398	5.2800	<0.0001	***
Cropland, 5 km buffer [%]	-2.1915	0.4470	-4.9020	<0.0001	***
Water, 5 km buffer [%]	0.9181	0.3119	2.9440	0.0032	**
Urban, 5 km buffer [%]	-1.4800	0.4783	-3.0940	0.0020	**
Distance to stream [m]	0.7341	0.1846	3.9760	<0.0001	***

Table D.9: Factors characterizing ESS cluster 2 and 5 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 2; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 5. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1912.3, df = 16, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small difference (χ^2 = 72.9, df = 3, p = 1.0e-15).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	-13.8425	0.9449	-14.6500	<0.0001	***
Topography and soil parameters					
Elevation [m]	10.2349	0.9931	10.3060	<0.0001	***
Slope [%]	1.9034	0.7526	2.5290	0.0114	*
Aspect [°]	-0.8473	0.2715	-3.1200	0.0018	**
Curvature [score]	10.2743	0.9209	11.1570	<0.0001	***
Effective rooting depth [mm]	6.6289	0.8505	7.7940	<0.0001	***
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	2.9127	0.6411	4.5430	<0.0001	***
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	-2.5054	0.9158	-2.7360	0.0062	**
Available water holding capacity [cm cm^{-1}]	15.5389	2.4739	6.2810	<0.0001	***
Soil quality index	-7.1422	1.1338	-6.2990	<0.0001	***
Climate					
Precipitation [mm]	-4.1262	0.5983	-6.8970	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	0.9847	0.5301	1.8580	0.0632	.
Landscape composition					
Forest, 5 km buffer [%]	3.2695	0.6201	5.2720	<0.0001	
SRC, 5 km buffer [%]	7.0331	0.4659	15.0950	<0.0001	***
Urban, 5 km buffer [%]	-3.5660	0.6424	-5.5510	<0.0001	***
Water, 5 km buffer [%]	3.5180	0.5055	6.9590	<0.0001	***
Distance to stream [m]	1.3894	0.3118	4.4550	<0.0001	***

Table D.10: Factors characterizing ESS cluster 2 and 6 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 2; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 6. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1710.2, df = 12, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed only a small and insignificant difference (χ^2 = 5.5, df = 3, p = 0.1).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	4.8578	0.6886	7.0550	<0.0001	***
Topography and soil parameters					
Slope [%]	-11.2392	0.5480	-20.5090	<0.0001	***
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	-1.7174	0.4896	-3.5080	0.0004	***
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	-2.2180	0.6798	-3.2630	0.0011	**
Effective rooting depth [mm]	-1.7088	0.6805	-2.5110	0.0120	*
Available water holding capacity [cm cm^{-1}]	-6.1165	0.9342	-6.5470	<0.0001	***
Soil quality index	1.4359	0.6994	2.0530	0.0400	*
Climate					
Precipitation [mm]	1.1270	0.3907	2.8850	0.0039	**
Reference Evapotranspiration [mm a^{-1}]	-2.4961	0.4376	-5.7040	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	0.9692	0.5344	1.8130	0.0698	.
SRC, 5 km buffer [%]	6.0974	0.4484	13.5990	<0.0001	***
Urban, 5 km buffer [%]	-3.9211	0.6047	-6.4850	<0.0001	***
Distance to stream [m]	1.0508	0.2580	4.0730	<0.0001	***

Table D.11: Factors characterizing ESS cluster 3 and 4 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 3; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 4. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1646.8, df = 16, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed a difference (χ^2 = 236.3, df = 3, p <2.2e-16).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	-9.1475	0.8358	-10.9450	<0.0001	***
Topography and soil parameters					
Elevation [m]	6.0154	0.7269	8.2750	<0.0001	***
Slope [%]	5.9011	0.5347	11.0360	<0.0001	***
Curvature [score]	2.5667	0.5402	4.7510	<0.0001	***
Effective rooting depth [mm]	2.0808	0.6827	3.0480	0.0023	**
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	2.9274	0.5185	5.6460	<0.0001	***
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	4.4358	0.8118	5.4640	<0.0001	***
Available water holding capacity [cm cm^{-1}]	4.6746	1.4258	3.2780	0.0010	**
Soil quality index	-4.8472	0.7893	-6.1410	<0.0001	***
Climate					
Precipitation [mm]	-3.4453	0.4665	-7.3860	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	4.4468	0.5105	8.7110	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	3.2055	0.6464	4.9590	<0.0001	***
Pasture, 5 km buffer [%]	-4.1189	0.4227	-9.7450	<0.0001	***
SRC, 5 km buffer [%]	-2.1360	0.4234	-5.0440	<0.0001	***
Urban, 5 km buffer [%]	-1.6754	0.6936	-2.4160	0.0157	*
Water, 5 km buffer [%]	1.7689	0.3180	5.5620	<0.0001	***
Distance to stream [m]	0.9010	0.2621	3.4380	0.0006	***

Table D.12: Factors characterizing ESS cluster 3 and 5 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 3; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 5. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1761.4, df = 14, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed a small difference (χ^2 = 55.3, df = 3, p = 5.9e-12).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	-18.2214	1.2309	-14.8040	<0.0001	***
Topography and soil parameters					
Slope [%]	7.5795	0.7841	9.6670	<0.0001	***
Curvature [score]	9.8788	0.8757	11.2810	<0.0001	***
Effective rooting depth [mm]	3.1985	0.6233	5.1320	<0.0001	***
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	3.4341	0.6891	4.9830	<0.0001	***
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	9.7706	1.1365	8.5970	<0.0001	***
Available water holding capacity [cm cm^{-1}]	4.7929	1.6248	2.9500	0.0032	**
Climate					
Precipitation [mm]	-4.0495	0.6254	-6.4750	<0.0001	***
Reference Evapotranspiration [mm a^{-1}]	3.6037	0.6621	5.4430	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	7.1610	0.9269	7.7260	<0.0001	***
Pasture, 5 km buffer [%]	-0.9041	0.5818	-1.5540	0.1202	
SRC, 5 km buffer [%]	2.5835	0.5658	4.5660	<0.0001	***
Urban, 5 km buffer [%]	-5.9464	0.8748	-6.7970	<0.0001	***
Water, 5 km buffer [%]	2.8066	0.4700	5.9720	<0.0001	***
Distance to stream [m]	1.0941	0.3834	2.8530	0.0043	**

Table D.13: Factors characterizing ESS cluster 3 and 6 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 3; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 6. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 813.5, df = 14, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed a difference (χ^2 = 160.1, df = 3, p <2.2e-16).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	-1.5289	0.7930	-1.9280	0.0539	.
Topography and soil parameters					
Elevation [m]	3.0177	0.7241	4.1670	<0.0001	***
Slope [%]	-2.4489	0.4227	-5.7930	<0.0001	***
Aspect [°]	0.3646	0.2336	1.5610	0.1185	
Curvature [score]	0.9358	0.4337	2.1580	0.0310	*
Effective rooting depth [mm]	1.1254	0.4434	2.5380	0.0111	*
Erosivity (R) [MJ mm ha^{-1} h^{-1} a^{-1}]	3.3980	0.7797	4.3580	<0.0001	***
Available water holding capacity [cm cm^{-1}]	-3.5013	0.6796	-5.1520	<0.0001	***
Climate					
Precipitation [mm]	-1.4466	0.4595	-3.1480	0.0016	**
Reference Evapotranspiration [mm a^{-1}]	0.8246	0.4345	1.8980	0.0577	.
Landscape composition					
Pasture, 5 km buffer [%]	-3.5496	0.3673	-9.6650	<0.0001	***
Cropland, 5 km buffer [%]	-0.6871	0.4512	-1.5230	0.1278	
Urban, 5 km buffer [%]	-6.7525	0.7074	-9.5450	<0.0001	***
Water, 5 km buffer [%]	1.2738	0.3021	4.2170	<0.0001	***
Distance to stream [m]	0.9859	0.2821	3.4950	0.0005	***

Table D.14: Factors characterizing ESS cluster 4 and 5 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 4; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 5. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1203.3, df = 10, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed a small difference (χ^2 = 37.0, df = 3, p= 4.9e-8).

Explanatory variable	**Stand.** β	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	-7.7021	0.5501	-14.0000	<0.0001	***
Topography and soil parameters					
Elevation [m]	4.3332	0.5428	7.9830	<0.0001	***
Slope [%]	2.6263	0.5686	4.6190	<0.0001	***
Curvature [score]	7.0915	0.6944	10.2130	<0.0001	***
Effective rooting depth [mm]	2.6274	0.3883	6.7660	<0.0001	***
Available water holding capacity [cm cm^{-1}]	8.9751	1.0756	8.3440	<0.0001	***
Climate					
Precipitation [mm]	-2.5840	0.4410	-5.8600	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	0.7941	0.4513	1.7600	0.0785	.
SRC, 5 km buffer [%]	3.7033	0.3259	11.3630	<0.0001	***
Urban, 5 km buffer [%]	-4.3034	0.4135	-10.4080	<0.0001	***
Water, 5 km buffer [%]	1.7223	0.3840	4.4850	<0.0001	***

Table D.15: Factors characterizing ESS cluster 4 and 6 for scenario 4 (backward logistic regression). A positive value for the standardized β indicates that an explanatory variable is contributing to cluster 4; a negative value for the standardized β indicates that an explanatory variable is contributing to cluster 6. The likelihood ratio test showed a significant difference when the final model was compared to a null model (χ^2 = 1169.6, df = 13, p <2.2e-16). Comparing the final model with a model including x- and y-coordinates, the likelihood ratio test showed a small difference (χ^2 = 10.7, df = 3, p= 0.01).

Explanatory variable	**Stand. β**	**SE**	**z value**	**Pr(>| z |)**	
(Intercept)	6.5561	0.6355	10.3170	<0.0001	***
Topography and soil parameters					
Elevation [m]	-3.9147	0.5301	-7.3840	<0.0001	***
Slope [%]	-9.3879	0.4530	-20.725	<0.0001	***
Effective rooting depth [mm]	-1.7020	0.6290	-2.7060	0.0068	**
Erodibility (K) [t ha h ha^{-1} MJ^{-1} mm^{-1}]	-2.1460	0.4473	-4.7980	<0.0001	***
Available water holding capacity [cm cm^{-1}]	-9.0053	1.3415	-6.7130	<0.0001	***
Soil quality index	4.0277	0.6951	5.7940	<0.0001	***
Climate					
Precipitation [mm]	1.3220	0.3994	3.3100	0.0009	***
Reference Evapotranspiration [mm a^{-1}]	-3.0745	0.3917	-7.8500	<0.0001	***
Landscape composition					
Forest, 5 km buffer [%]	-1.4619	0.5193	-2.8150	0.0049	**
Pasture, 5 km buffer [%]	1.5603	0.3778	4.1300	<0.0001	***
SRC, 5 km buffer [%]	2.5940	0.3260	7.9560	<0.0001	***
Urban, 5 km buffer [%]	-3.1592	0.5041	-6.2670	<0.0001	***
Water, 5 km buffer [%]	-0.7262	0.3089	-2.3510	0.0187	*

E

APPENDIX OF CHAPTER 4

This appendix contains the full model description of the ecological-economic rangeland model that is used in Chapter 4 of this thesis. It is listed as supplementary material for the publication: Schulze, J., Frank, K., Müller, B. (2016). Governmental response to climate risk: model-based assessment of livestock supplementation in drylands. Land Use Policy 54, 47-57.

The model used within this study is a modified version of the generic, ecological-economic simulation model described in Müller et al. (2015). The model description follows the ODD protocol for describing individual- and agent-based models (Grimm et al., 2006, 2010). The first three elements of the description provide an overview and the remaining elements give details on the model structure.

E.1 PURPOSE

The model was developed to analyze the ecological and economic implications of different supplementation strategies in the form of subsidies provided by the government on a semi-arid rangeland system and to detect supplementation strategies which are ecologically and economically sustainable.

E.2 ENTITIES, STATE VARIABLES AND SCALES

For simplicity, we model one livestock-breeding household possessing one herd of sheep. The household depends exclusively on livestock production for its livelihood. It is assumed that no purchase of livestock takes place. Hence, herd growth is driven solely by birth processes. The interrelated processes between livestock and vegetation dynamics are simulated for a time horizon T of 60 years. The model runs in annual time steps. The investigated pasture is homogeneous. Table E.1 shows the state variables of the model.

The ecological model part of the stylized semi-arid rangeland corresponds to the ecological model described in Martin et al. (2014). As is common for semi-arid ecosystem (Linstädter and Baumann, 2013; Ruppert et al., 2012) the main driver

Table E.1: Set of state variables in the model.

Entity	State variables	Symbol	Unit
Precipitation	Annual rainfall	r_t	[mm]
Pasture	Reserve biomass	R_t	[kg]
	Green biomass	G_t	[kg]
	Green biomass not grazed	$G_{over,t}$	[kg]
Livestock	Herd size	S_t	[sheep]
	Number of livestock to destock	D_t	[sheep]
	Supplemented number of livestock	$S_{supp,t}$	[sheep]

of forage dynamics is annual precipitation. The pasture is assumed to consist of an abstract perennial plant type (i.e., perennial grasses or shrubs), where all aboveground parts are accessible to smallstock. This perennial plant type is characterized by two functional parts: green and reserve biomass (Müller et al., 2007; Martin et al., 2014). The term green biomass refers to all photosynthetic active parts of aboveground biomass, which is assumed to constitute the main forage resource for livestock. Reserve biomass describes the non-photosynthetically reserve biomass (either below- or above-ground) which serves as storage (termed after Noy-Meir (1982)). Reserve biomass is influenced by rainfall and by grazing management history (O'Connor, 1991). Livestock is modeled as one herd of sheep characterized by its size. The management strategy that is applied during the whole time span is characterized by when and for which purpose supplementary feeding for livestock is granted (e.g., for pasture regeneration or for maintenance of livestock).

E.3 PROCESS OVERVIEW AND SCHEDULING

Here, the processes of the model are briefly specified to give a general overview of the model and its dynamics (cf. Figure E.1). For a detailed description of each of the processes, see Section E.6 Submodels. The processes are presented according to their sequence within one time step.

Process 1: Rainfall. The rainfall for each year is randomly sampled from a log-normal distribution.

Process 2: Dynamics of green biomass. The green biomass is determined by two variables: rainfall and current reserve biomass.

Process 3: Livestock. Animals are born at a constant birth rate. Following birth, we calculate the number of animals that need to be sold because of lack of forage on the pasture. In process 3 we calculate the livestock numbers without possible supplementation and readjust in process 4, depending on the specific supplementation strategy.

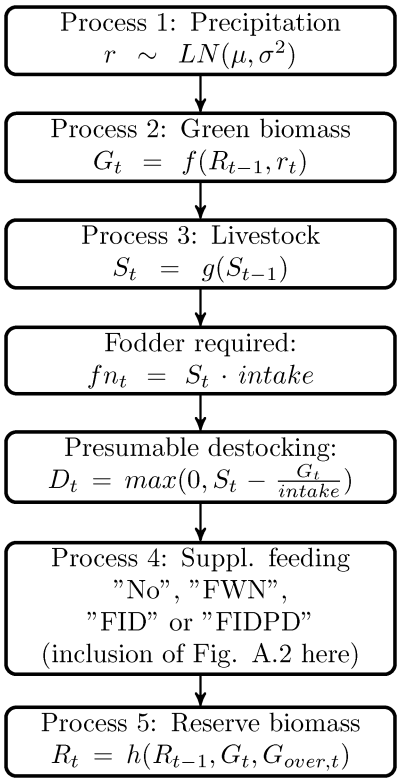

Figure E.1: The schedule of the processes of the model during one year. Explanation of abbreviations: "No": without supplementation; "FWN": supplementary feeding when natural forage is not sufficient; "FID": supplementary feeding in drought to avoid destocking; "FIDPD": supplementary feeding in drought to avoid destocking and after supplementation to relieve pasture.

Process 4: Supplementary feeding. Three supplementation strategies are compared to the case without supplementation. According to the supplementation strategy and the current rainfall it is determined how many animals are being supplemented (either to avoid decreasing herd size or to rest the pasture). Livestock numbers and vegetation are adjusted accordingly.

Process 5: Dynamics of reserve biomass. At the end of a time step, the reserve biomass is adjusted depending on the portion of the pasture grazed and by taking natural decay into account.

E.4 DESIGN CONCEPTS

Basic principles: In this paragraph, it is mentioned which general concepts, theories, hypotheses or modeling approaches are underlying the model's design (see Grimm et al. (2010)).

Modeling approach: We use a stylized model, which is explicit in representing the main features of a semi-arid rangeland system, but is simple enough to demonstrate the consequences of different supplementation strategies (Schlüter et al., 2013).

Farmer's criterion for decision-making: We assume that the farmer adapts his herd to the available forage (incl. supplementary feeding) always keeping as many animals as possible. Therewith, we follow insights from studies on pastoral systems in Africa that showed that keeping large herds acts as an insurance against environmental shocks (Lybbert et al., 2004; Robinson and Berkes, 2010). This represents a major difference to the model presented in Müller et al. (2015), where the decision model builds up on the concept of "minimum viable herd size".

Ecological approach: We follow the non-equilibrium theory for rangeland science which implies that the carrying capacity concept is inadequate for grazing management in semi-arid and arid areas. Livestock numbers rarely reach equilibrium with their fluctuating resource base (cf. Vetter et al., 2005). Hence in contrast to a fixed stocking density the adaptation of livestock numbers to varying forage availability is better suited under these environments (cf. Vetter et al., 2005; von Wehrden et al., 2012). Therefore, in our model livestock numbers are adjusted to forage on the pasture in each year.

Social-ecological approach: We start from the perspective of "Ecosystem-stewardship" (cf. Chapin et al., 2010). That means, we take into account social-ecological interdependencies of human activities and ecosystem services. We are interested to detect proactive strategies (such as appropriate supplementary feeding strategies), which manage change and enhance the adaptive capacity and resilience of the social-ecological system.

Beside these basic principles, the ODD protocol asks for further design concepts. Here, we focus only on those that are relevant for the presented model:

Adaptation: Each year the farmer adapts the herd size according to the amount of forage available (incl. supplementary feeding).

Objectives: Each year the farmer tries to keep as many livestock as possible and follows a certain fixed supplementation strategy throughout the entire time span.

Prediction: The farmer cannot predict future forage production.

Sensing: The farmer knows herd size, the available forage, the available amount of supplementary fodder, precipitation in the current and/or the past year, and whether supplementation was granted in the previous year or not.

Stochasticity: Annual rainfall is drawn from a random log-normal distribution.

Observation: Annual livestock numbers, amounts of supplementary feeding and the state of the pasture (via reserve biomass) are recorded for the assessment of the different supplementation strategies.

E.5 INITIALISATION

In the first year the reserve biomass, is initialized as a defined proportion R_0 (here 33% see Table E.2 of the maximal amount of reserve biomass per hectare $R_{max}(R_0 \cdot R_{max})$. Green biomass and resulting sheep number are calculated from the initial value of the reserve biomass in the first time step. In the initial year, the livestock is adapted to the available forage and no grazing takes place.

E.6 SUBMODELS

Again, the processes are presented according to their sequence within one time step and visualized in Figure E.1 and E.2.

Process 1: Rainfall. The rainfall is characterized by a low annual mean μ and a high variability σ. Annual rainfall r_t follows a log-normal distribution. With this right-skewed distribution events of low rainfall are frequent, while high rainfall events are seldom but can occur. There is no correlation assumed in rainfall between consecutive years.

Process 2: Dynamics of green biomass. To calculate the dynamics of green biomass G_t, we used the approach proposed by Müller et al. (2007) and further developed in Martin et al. (2014):

$$G_t = min(\lambda \cdot R_{t-1}, r_t \cdot RUE_{R \to G} \cdot R_{t-1}) \tag{E.1}$$

with r_t denoting the precipitation, $RUE_{R \to G}$ rain use efficiency and R_{t-1} reserve biomass (for parameter values see Table E.2).

G_t is influenced by the precipitation r_t in the current year. It has a strong impact on the formation of green biomass out of available reserve biomass R_{t-1}. This process is quantified by the specific rain use efficiency parameter $RUE_{R \to G}$ for green biomass from reserve biomass in units of $kgG \cdot (kgR \cdot mm)^{-1} = mm^{-1}$. In Müller et al. (2015) and Martin et al. (2014) a further factor influenced the green biomass: the green biomass left over from the preceding year $G_{over,t-1}$. Those models were calibrated on specific case studies in Morocco where evergreen plants were found. In contrast, we did not include this factor in the present model to foster generality of model results as the majority of drylands consists of deciduous plants. The threshold λ of $\frac{G_t}{R_{t-1}}$ denotes a capacity limit on how much green biomass G_t may grow from reserve biomass R_{t-1}. A low λ signifies a more woody plant functional type whereas a high λ signifies a grass type. For the parameter values we refer to Table E.2.

Process 3: Livestock. Firstly, the herd size increases with a constant birth rate b. Following birth, we calculate the number of animals that need to be sold because of lack of forage on the pasture. If the forage on the pasture is not sufficient, the amount which would be needed to be destocked D_t is determined by:

$$D_t = max\left(0, S_t - \frac{G_t}{intake}\right) \tag{E.2}$$

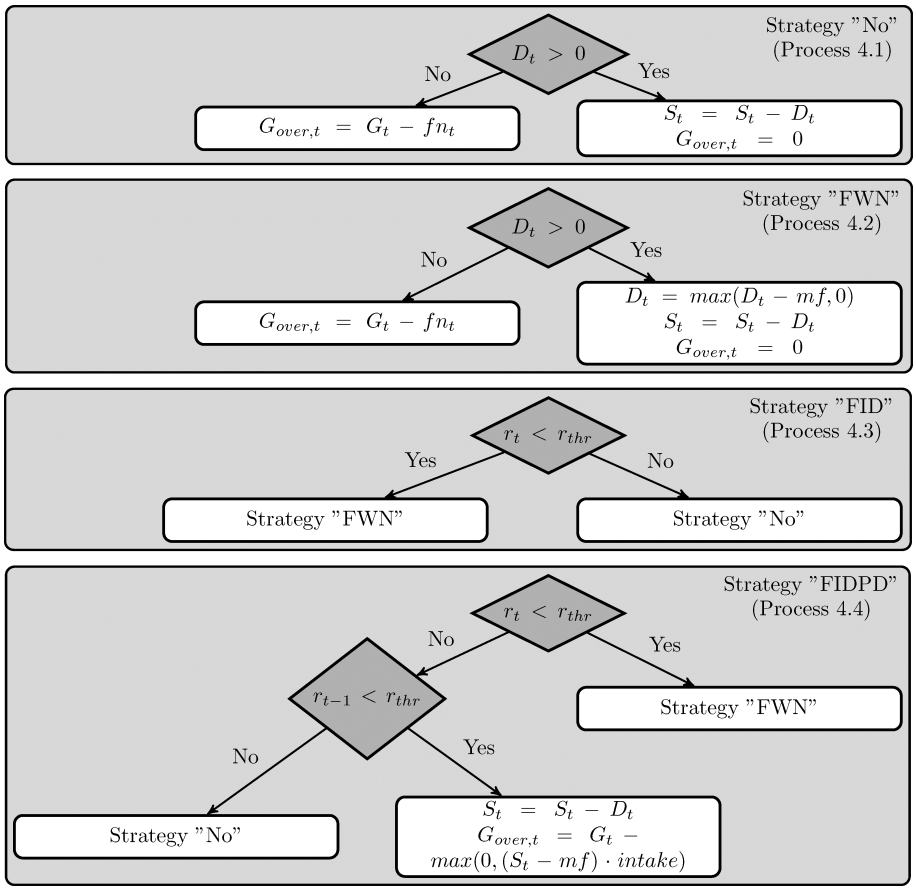

Figure E.2: Specification of the scheduling of process 4. Explanation of abbreviations: "No": without supplementation; "FWN": supplementary feeding when natural forage is not sufficient; "FID": supplementary feeding in drought to avoid destocking; "FIDPD": supplementary feeding in drought to avoid destocking and after supplementation to relieve pasture.

We assume that the farmer adjusts herd size to the amount of available green biomass. However, in the case that all green biomass is used, it cannot be excluded that also other parts of the plants - here reserve biomass - is eaten (see below process "Dynamics of reserve biomass"). Natural death and animal condition are not explicitly modeled because it is assumed that older animals and animals with bad condition are sold first. In the next process, the amount of presumable destocking D_t (necessary due to natural fodder shortage) may be reduced in dependence on how supplementation is carried out.

Process 4: Supplementary feeding. In this study, supplementation is regarded as subsidy given by the government as it is practiced in many pastoralist systems in drylands. Therefore, supplementary feeding strategies in this study are not constrained to the financial situation of the farmer, but are constrained to the economic willingness of the grantor to support the pastoralist.

As many central subsidy decisions are based on traceable measures, for instance climatic properties, we incorporate subsidized supplementary feeding strategies that are granted based on the current precipitation. At this, we incorporate strategies where supplements are granted during and after droughts. A drought occurs when current precipitation falls below a previously fixed rain threshold (r_{thr}). The strategies differ in the way how supplements are used (i.e., to avoid destocking or to rest the pasture).

The following four main strategies that are being investigated are (cf. Figure E.2):

Process 4.1: No supplementation ("No feeding"; short "No"). Since there is no possibility to avoid destocking due to forage shortage, the sale of the animals D_t is carried out. The herd size is being adapted and the remaining green biomass is set to zero.

Process 4.2: Supplementary feeding when natural forage is not sufficient ("Feeding when needed"; short "FWN"). Supplementation would be carried out in the following case: animals would have to be sold because lack of fodder ($D_t > 0$) on the pasture. In this case, it is being calculated how many animals can be saved by the available supplements:

$$S_{supp,t} = min(mf, D_t) \tag{E.3}$$

Subsequently, herd size is being adapted and the remaining green biomass is set to zero.

Process 4.3: Supplementary feeding in drought to avoid destocking ("Feeding in drought"; short "FID"). Supplementation would be carried out in the following case: animals would have to be sold because of lack of fodder ($D_t > 0$) on the pasture and the current amount of precipitation is below the threshold (r_{thr}). In this case, it is calculated how many animals can be saved by the available supplements (see equation E.3). Subsequently, herd size is being adapted and the remaining green biomass is set to zero.

Process 4.4: Supplementary feeding in drought to avoid destocking and after the drought to relieve pasture ("Feeding in drought and post-drought"; short "FIDPD"). Three types of years occur (in latter two supplementation is needed):

1. No animals have to be sold because of lack of fodder ($D_t = 0$). Hence, no supplements are needed. The green biomass over is being calculated.

2. Animals would have to be sold because of lack of fodder on pasture ($D_t > 0$) and current amount of precipitation is below the threshold ($r_t < r_{thr}$). Herd size is being adapted and the remaining green biomass is set to zero (according to the described processes for strategy "Feeding in drought").

3. In the preceding year the amount of precipitation was below the threshold ($r_{t-1} < r_{thr}$). In this case, no avoidance of destocking takes place. Instead, as many animals as possible remaining on the farm after destocking are fed by

supplementary fodder in order to rest the pasture. This is constrained by the available amount of supplementary fodder mf. Therefore, herd size is reduced by D_t and the remaining green biomass is calculated taken this adapted herd size and the available supplementary fodder into account.

For each of the main strategies the rain threshold (r_{thr}) and the maximal amount of supplements (mf) are set at the beginning of a simulation, representing the willingness of the grantor how often and how much to grant supplements. Therefore, besides comparing the four main supplementary feeding strategies, the effect of different heights and frequencies of supplementation were investigated.

Process 5: Dynamics of reserve biomass. Current reserve biomass R_t is calculated by:

$$R_t = \begin{cases} (1 - m_{res}) \cdot R_{t-1} + w \cdot (1 - d \cdot R_{t-1}) & \\ \qquad \cdot (gr_1 \cdot (G_t - G_{over,t}) + G_{over,t}) & \text{, if } G_{over,t} > 0 \\ (1 - m_{res} - gr_2) \cdot R_{t-1} + w \cdot (1 - d \cdot R_{t-1}) \cdot gr_1 \cdot G_t & \text{, if } G_{over,t} = 0 \end{cases} \tag{E.4}$$

with w denoting the recovery rate, gr_1 harshness of grazing, gr_2 direct take-off rate of reserve biomass by grazing, m_{res} mortality rate of reserve biomass and $G_{over,t}$ the green biomass not grazed (for parameter values see Table E.2).

In detail: R_t depends on its state in the past year R_{t-1} reduced by mortality (via a mortality rate $0 \leq m_{res} \leq 1$). If sufficient green biomass is no longer available as forage, a portion of reserve biomass ($gr_2 \cdot R_{t-1}$) is lost due to grazing. When green biomass becomes rare, the pressure on the reserve biomass increases. Due to simplicity reasons, this is assumed to be a constant term independent from the current herd size. This last process was not included in the model by Müller et al. (2007).

Besides gr_2, grazing has another effect. This is the parameter harshness of grazing $gr_1 \in [0,1]$. Here, the following dependency holds: the higher gr_1, the lower the impact of grazing. While no density dependence is assumed for the growth of green biomass G_t, it is included in the dynamics of reserve biomass R_t. It is incorporated by the parameter d given by

$$d = \frac{1}{area \cdot R_{max}} \tag{E.5}$$

where R_{max} is the maximal amount of reserve biomass per hectare in kg and $area$ the size of the pasture in hectares. As green biomass production also depends on reserve biomass, growth is indirectly limited by plant competition.

Parameter set

All parameters used in the model, their values, their ranges in the sensitivity analysis and if available the references for their parameterization are shown in Table E.2.

For the specific rain use efficiency $RUE_{R \to G}$, the maximum proportion of green to reserve biomass λ as well as for rainfall characteristics (mean annual rainfall and its

standard deviation), we used data from a case study in Morocco (Baumann, 2009; Steinschulte, 2011; Linstädter and Baumann, 2013; Linstädter et al., 2013). The fodder value of pasture vegetation is assumed to be 0.5 fodder units (FU) per kg dry matter (derived from published data for the dominant shrub species Artemisia herba-alba; using approximately the mean value between 0.35 FU cited in Acherkouk and El Houmaizi (2013, p. 76) and 0.63 FU cited in Houmani et al. (2004, p. 169). Considering 320 FU as the average demand per sheep and year (Lazarev, 2008), a value of 640 kg per sheep is derived for the parameter *intake*.

The following parameters were chosen based on data collected in Morocco. The birth rate of sheep was parameterized using data from Chaarani and Mahi (2009), which states a birth rate of 0.7390 lambs per ewe. It is assumed that male sheep were sold first and the herd consists to a large extent of female sheep. After rounding up, a total birth rate of 0.8 was used in the simulation.

The price for purchase of fodder for one year for one animal pf is given in relation to the price for the sale of one animal. Chaarani and Mahi (2009) state a sales price of 700 Dh per ewe (Dh = Moroccan Dirham) and note as price for barley for supplementation 3Dh kg^{-1}. The following applies to barley: 1 kg barley corresponds to one 1 FU (FU = fodder unit). Since 320 FU are needed per year per sheep (Lazarev, 2008), the annual costs for supplementation amount to $3 \cdot 320 = 960Dh$ per animal and hence $pf = \frac{960}{700} \approx 1.3$ times the price obtained for selling one sheep. We conducted parameter variation to adjust the remaining ecological parameters (such as w, gr_1) to result in realistic empirical patterns (see Schulze, 2011).

Table E.2: List of parameters, default parameter set, ranges in sensitivity analysis (SA) and if available references.

Parameter	Abbreviation	Unit	Value	SA	Reference
Ecological parameters					
Recovery rate of reserve biomass	w	unitless (rate)	0.8	0-1	Schulze (2011)
Specific rain use efficiency	$RUE_{R\rightarrow G}$	[1/mm]	0.002		Steinschulte (2011)
Mortality rate of reserve biomass	m_{res}	unitless (rate)	0.05		Schulze (2011)
Harshness of grazing	gr_1	unitless (rate)	0.5		Schulze (2011)
Direct take-off rate of reserve biomass by grazing	gr_2	unitless (rate)	0.1		Schulze (2011)
Maximum proportion of green to reserve biomass	λ	unitless (ratio)	0.5		Steinschulte (2011)
Maximal reserve biomass	R_{max}	[kg/ha]	1500		Schulze (2011)
Initial reserve biomass as the ratio of maximal coverage	R_0	unitless (rate)	0.333		
Area of the pasture	*area*	[ha]	500		
Livestock related parameters					
Fodder intake per sheep per year	*intake*	[kg]	640		Lazarev (2008); Acherkouk and El Houmaizi (2013); Houmani et al. (2004)
Birth rate of sheep	b	unitless (rate)	0.8	0.3-1.9	Chaarani and Mahi (2009)

Climatic parameters					
Mean annual rainfall	μ	[mm]	200		Linstädter and Baumann (2013)
Standard deviation of annual rainfall	σ	[mm]	100		Linstädter and Baumann (2013)
Technical parameters					
Time horizon in years	T	60			
Number of simulation	$simnumb$	500			
Economic parameters					
Rain threshold feeding	r_{thr}	[mm]	100	50-200	
Amount of feeding	mf	[sheep]	50	0-100	
Price of fodder for one sheep for one year	pf	unitless (rate)	1.3		Chaarani and Mahi (2009)

F

APPENDIX 1 OF CHAPTER 5

This appendix contains the Overview, Design concepts and Details (ODD) of the simulation model underlying the serious online game LandYOUs presented in Chapter 5 of this thesis. It is listed as supplementary material for the publication: Schulze, J., Martin, R., Finger, A., Henzen, C., Lindner, M., Pietzsch, K., Werntze, A., Zander, U., Seppelt, R. (2015). Design, implementation and test of a serious online game for exploring complex relationships of sustainable land management and human well-being. Environmental Modelling and Software 65, 58-66. In addition, it is an independent document accessible at figshare.com: Overview, Design concepts and Details (ODD) of the simulation model for the serious online game LandYOUs. Jule Schulze, Romina Martin, Ralf Seppelt. https://dx.doi.org/10.6084/m9.figshare.1119321.v5.

This appendix is providing all information necessary to in-depth understand the model underlying the LandYOUs game[1]. It follows the ODD (Overview, Design concepts, Details) protocol as suggested in Grimm et al. (2006, 2010) and focuses specifically on the underlying model feedbacks of the spatially explicit model. The LandYOUs online computer game is implemented based on the GISCAME[2] framework. Here, we do not report on the technical issues of GISCAME, which can be found in Fürst et al. (2010a,b, 2013).

1 www.landyous.org
2 www.giscame.com

F.1 PURPOSE

The model was developed as a basis for the educational online game LandYOUs. The aim of LandYOUs is to demonstrate various options and feedbacks of sustainable land management to the interested public, students and stakeholders. The core idea of the game LandYOUs is to provide a very aggregated system dynamics model with a reduced number of state variables, which get input from a spatially explicit map representing land use. Furthermore, the aim is to introduce various dynamic patterns due to nonlinear feedbacks. Although very much aggregated, the model should be capable of qualitatively capturing real world patterns, e.g., reproducing reasonable patterns according to Grimm et al. (2005).

F.2 ENTITIES, STATE VARIABLES AND SCALES

General notations:

- State variables and indicators, e.g., all time-dependent variables are denoted with captial letters X.
- Parameters are specified by small letters x.
- Dependencies to land use types LUT or any other functional dependency is denoted by $x(\cdot)$ or $X(\cdot)$.
- A reference to a grid cell i from a map is denoted by the subscript x_i or X_i.
- In the rare case that we need to refer to the recent and or previous time step t or $t-1$ also the subscript is used, if necessary delimited by a comma X_t, X_{t-1}, $X_{i,t}$.

The simulated country is represented by two elements: a map of a landscape and a set of indicators. The landscape consists of a regular grid of 100·100 cells, which can be assigned to different land covers:

- water bodies (wa),
- cropland (cr),
- forest (fo),
- settlement (st),
- fallow land (fa) or
- nature reserves (nr).

Land use is characterized by further indicators, such as site-specific conditions (e.g., fertility), landscape configuration and prior use (see Figure F.1 and Table F.1).

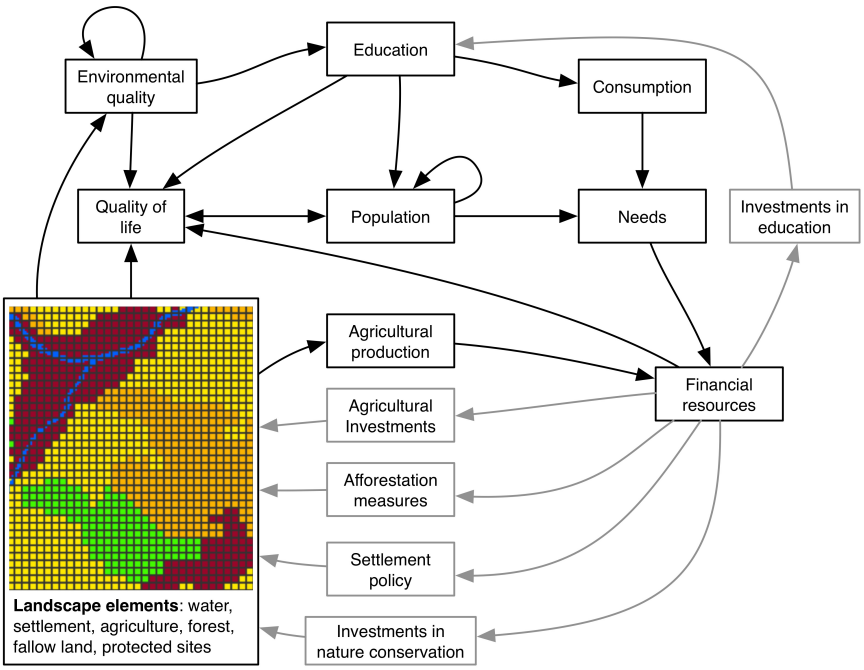

Figure F.1: Feedback system: State variables or indicators are plotted in black, investments and their impacts on the state variables in gray. The state variables of agricultural production, environmental quality and quality of life are derived from the spatially explicit configuration of the landscape elements.

A set of eight indicators captures the social, ecological and economic situation of the country (see Table F.1 for all indicators). Indicators are based on functional relationships between the map of the landscape and the indicators as well as between the indicators themselves. The player controls the landscape and the set of indicators by financial investments in different policy options.

The interrelated processes between investment decisions, landscape and indicators are simulated for a time horizon of maximal 10 time steps (rounds), where one time step resembles approximately 5 years of governance. Table F.1 shows all state variables of the model.

Table F.1: State variables of the model.

State variable	Symbol	Range
Global indicators/state variables (non-spatial)		
Agricultural production	AP	$[0, 10]$
Financial resources	FR	$]-\infty, \infty[$
Needs	Nd	$[0, 10]$
Consumption	Con	$[0, 10]$
Education	Ed	$[0, 10]$
Quality of life	QL	$[0, 10]$
Population	Pop	$[0, 10]$
Environmental quality	EQ	$[0, 10]$
Attributes of a grid cell i		
Land use type	LUT_i	*wa,cr,fo,st,fa,nr*
Direct neighborhood impact on environmental quality	IEQ_i	$[0, 1]$
Direct neighborhood impact on productivity	IP_i	$[0, 1]$
Extended neighborhood impact on quality of life	IQL_i	$[0, \frac{41}{60}]$
Productivity	P_i	$[0, 1]$
Environmental quality	EQ_i	$[0, 1]$
Quality of life	QL_i	$[0, \frac{41}{60}]$
Maximal population capacity	$PC_{max,i}$	$[0.004, 0.014]$
Site-specific potential	SP_i	$[0, 1]$
Prior use	PU_i	$[0, 1]$
Summary statistics of landscape		
Number of water bodies	N_{wa}	200
Number of cropland	N_{cr}	$[0, 10000]$
Number of forests	N_{fo}	$[0, 10000]$
Number of settlement	N_{st}	$[0, 10000]$
Number of fallow land	N_{fa}	$[0, 10000]$
Number of nature reserves	N_{nr}	$[0, 10000]$
Total size of landscape	N	10000
External drivers: variables of global market		
Market price	Pr	$[0, 10]$
Trade (import, export)	Tr	$[-10, 10]$
Variables of policy measures, control variables		
Agricultural investments	ID_{AP}	$[0, 50]$
Settlement policy	ID_{SeP}	$[0, 50]$
Afforestation measures	ID_{AF}	$[0, 50]$
Investment in nature conservation	ID_{NC}	$[-10\%, +10\%]$
Investment in education	ID_{Ed}	$[0, 50]$
Score	S	> 0

F.3 PROCESS OVERVIEW AND SCHEDULING

The main processes of the model according to their sequence within one time step are shortly described in this section. Section F.7 below then reports in detail on processes and feedbacks. The main processes comprise:

1. Initialization process in the first time step
2. Player's action: choosing investments for land use and education
3. Consequences of player's action on landscape and education
4. Calculation of indicators based on changed landscape
5. Indicator feedbacks, external effects and market dynamics
6. Calculation of score

F.3.1 *Initialization process*

This step takes place in the initial phase after starting the game. All subsequent rounds of the game, e.g., following time steps, start with processes described in Section F.3.2.

For each cell on the landscape the potential productivity, environmental quality and quality of life are calculated (for details on this and the following see Section F.7.1). Hereby, site-specific conditions (e.g., fertility, prior use) and neighboring effects are incorporated. This potential characteristic of a cell is complemented by the actual land cover of that cell. These two characteristics (potential and land cover) combined determine the actual condition (i.e., environmental quality, quality of life and productivity) of the cell. Based on these actual conditions of the cells, the indicators productivity, environmental quality and quality of life on the system level are calculated. All remaining indicators are set to the initial values given in Table F.2. Needs are then calculated based on the indicators population and consumption. Finally, the market price for the first year is determined by the relation of needs and agricultural production.

Table F.2: Initial state of the model.

Entity	State variables	Initial value
Landscape	Percentage of settlement	12%
	Percentage of water bodies	3%
	Percentage of agricultural area	50%
	Percentage of forests	17%
	Percentage of fallow land	11%
	Percentage of nature reserves	7%
	Previous environmental quality $EQ_{t=0}$	3
Indicators	Education Ed	3
	Consumption Con	5
	Population Pop	4
	Financial resources FR	80
Grid cell i	Maximal population capacity $PC_{max,i}$	0.004
	Prior use PU_i	current use

F.3.2 *Player's action: choosing investments for land use and education*

The player can invest financial resources in the five different policy options:

- Agricultural investments (ID_{AP})
- Settlement policy (ID_{SeP})
- Afforestation measures (ID_{AF})
- Investment in nature conservation (ID_{NC})
- Investment in education (ID_{Ed})

The following Section F.3.3 shortly describes the consequences of the player's actions (for details see Sections F.7.2 and F.7.3).

F.3.3 *Consequences of player's action*

Land use change is primarily driven by the investment decisions of the player, but also by market conditions and the current population size.

1. Areas of nature reserves are decreased or increased based on a chosen percentage by the player. At this, potential environmental quality of the cells determines which cells are to be changed (for details on this and the following see F.7.3).

2. Investment in settlement policy determines the maximal population capacity of settlement cells. Based on this capacity and the current population size, the number of necessary additional settlement cells is calculated. The potential quality of life of possible cells determines which cells are to be changed.

3. The shares of agricultural land, forests and fallow land are determined by the financial support of agriculture and forestry and the current market prices. It is assumed that decisions on land use change taken by the people in the governed country are driven by the objective of income maximization.

4. The fifth policy instrument, investment in education, does not influence the landscape but directly influences the indicator education.

F.3.4 *Calculation of indicators based on changed landscape*

After updating the landscape, we calculate those indicators that are directly influenced by the landscape: agricultural production, quality of life and environmental quality. Here, site-specific potentials (e.g., fertility), prior use, and landscape configuration (via neighboring effects) are taken into account (for details see Section F.7.4).

F.3.5 *Indicator feedbacks, external effects and market dynamics*

Indicators are updated based on a set of nonlinear functional relationships between them (for details see Section F.7.5).

Additionally, the market price for agricultural products is calculated based on the current needs and agricultural production (for details see Section F.7.5). A possible deviation to this market price due to external effects is determined: in three out of ten rounds of the game the market price is randomly increased or decreased by up to 100%. Hereby, sudden changes in global markets and their impact on the national economy are incorporated into the game. Financial resources of the player are calculated, which finally influence the quality of life again (for details see Section F.7.5 and Figure F.3).

F.3.6 *Calculation of score*

At the end of each round, it is checked whether exit conditions occur (i.e., minimal quality of life or environmental quality) or additional bonus points are obtained (i.e., maximal quality of life and environmental quality). Finally, the score is updated based on possible bonus points and the indicators quality of life, environmental quality and financial resources (for details see Section F.7.6).

F.4 DESIGN CONCEPTS

Basic principles: The presented model is implemented as time-discrete system-dynamics model. It is complemented by an spatially explicit landscape represented by cells in a regular grid.

The spatial explicitness of the model allows to incorporate aspects of landscape configuration. These are assumed to impact the environmental quality, the quality of life and the productivity of landscapes. For example, the quality of life is determined by evaluating the surroundings of the settlement areas: forests, water bodies and protected sites near settlements positively influence quality of life due to their recreational purposes.

The feedbacks between various indicators are calculated by nonlinear functions, which are coded in accordance with findings from recent literature. For details on specific relationships see Section F.7.5.

In the model, land use change concerning agricultural production and forestry is based on the concept of profit maximization. For this, market prices in the model are determined by supply and demand, a standard assumption in economic theory (Mankiw and Taylor, 2006).

Being the basis for an educational game comes along with requirements for the underlying model. To support the player's perception and understanding of state variables, indicators in the model are normalized (range between 0 and 10). Hence, the feedbacks do not correspond with quantitative representations of the real world. Therefore, the underlying model of LandYOUs cannot be tested against real world data, as documented by Bennett et al. (2013). However, the model captures real world feedbacks in a realistic way and reproduces qualitative relationships as required by Grimm et al. (2005).

The underlying model of a serious game needs to be robust even with extreme investment decisions resulting in unrealistic land use patterns and indicators. Players sometimes wish to test the model behaviour in extreme situations, such as no investments in agricultural production and forests or increasing the area of nature conservation sites up to 100%. In these cases, the LandYOUs model also reproduces qualitatively plausible pattern, although such situations might never be found in real world. In fact, most of these situations lead to game end, for instance, because of unacceptable conditions in quality of life.

Beside these basic principles, the ODD protocol asks for further design concepts. Here, we focus only on those that are relevant for the model underlying the LandYOUs game:

Emergence: Site-dependent characteristics are updated for each cell based on its neighborhood and prior use (see Section F.7.1 for details). This results in preferences for land use changes and the final number of cells for each type.

Objectives: The player should try to maximize environmental quality, financial resources and quality of life at the same time, which altogether maximizes its score.

Learning: No learning is simulated in the model, but we expect learning to happen with the player. Through careful observation of land use and indicator changes, the player might understand causes for trends and may support or counteract those via targeted investments.
Prediction: Predicting the consequences of chosen investments depends very much on the understanding of the player. One can see the current market price to estimate the effects on profits from agriculture. Depending on this, one can support or counteract for example further price increases by appropriate investment into agricultural production.
Sensing: The player receives update messages after each round for all significant indicator changes. Further, one can observe all indicator developments over the past rounds. Changes of market price can be requested via an extra button.
Interaction: There is no interaction between players right now, but a multi-player version is intended for future updates.
Stochasticity: For an exciting gaming experience, variations between games should be ensured. Therefore, several random processes are incorporated in the model. Site-dependent conditions over the landscape as well as site-independent characteristics of different land use types are randomly set at the beginning of each game. Furthermore, deviations of the market price randomly occur over the 10 rounds. Thereby, sudden changes in global markets and their impact on the national economy are incorporated into the game.
Observation: For model testing, emerging land use patterns and indicator values were collected and analyzed with regard to their link to players actions. The aim was that the model should result in realistic land use patterns (e.g., a spatial correlation of settlement cells). Furthermore, the outcome of the model should appropriately respond to the action of the player (e.g., investment in agricultural production should lead to an increase of productivity).

F.5 INITIALIZATION

At the beginning of a simulation (i.e., one game), the landscape is initialized based on the percentages given in Table F.2. The configuration of the landscape is the same for all simulations. It is a virtual landscape that does not represent a specific region. Furthermore, indicators values are set to initial values (see Table F.2). Finally, the maximal population capacity per cell is set to its initial value (see Table F.2) and the memory of prior uses of cells are set to the current land use type in each cell. All other initial variables are then calculated based on the processes described in Section F.7.

F.6 INPUT DATA

No input data is used.

F.7 SUBMODELS

In this section, the processes of the model according to their sequence in one time step are described in detail. Tables F.3, F.4, and F.5 show all parameters and their standard values needed for the calculation of processes in this section. Additionally, Figure F.4, to be find at the end of the document, shows the model interface where all parameters and the feedbacks between the indicators can be set. Values for the productivity, environmental quality and quality of life of the different land use types on the cell level are randomly set (i.e., varying fixed values by +/- 2%) at the beginning of the simulation.

F.7.1 *Initialization process*

Here we start with documenting the initial time step. Each of the subsequent time steps starts with process F.7.2.

In the initialization process Equation F.1 through F.11 are calculated for starting the first round of game. In each round of the game and even in interims steps, Equations F.1 through F.11 are again used for updating land use on the landscape and state variables according to player's investment decisions (see Section F.7.3 and F.7.4).

For each cell on the landscape, the impact on its potential environmental quality and productivity of its neighborhood is calculated. For cell i, the direct neighborhood impact on the environmental quality IEQ_i is influenced by the number of water bodies and nature reserves in the moore neighborhood (i.e., comprising the eight surrounding cells):

$$IEQ_i = \frac{1}{|M(i)|} \cdot \sum_{\substack{j \in M(i) \\ LUT_j \in \{wa,nr\}}} imp_{EQ}(LUT_j) \tag{F.1}$$

where $M(i)$ denotes all cells in the moore neighborhood of cell i, e.g., the cells j directly adjacent to cell i. $imp_{EQ}(LUT_j)$ is the impact factor on environmental quality of the land use type LUT_j of neighbor cells j, see Table F.4, and $|M(i)|$ denotes the size, e.g., number of cells, of the moore neighborhood $M(i)$, which are 8 but differ for cells at the edge of the landscape map.

Similarly, for cell i, the direct neighborhood impact on the productivity IP_i is influenced by the number of water bodies and nature reserves in the moore neighborhood (i.e., comprising the eight surrounding cells):

$$IP_i = \frac{1}{|M(i)|} \cdot \sum_{\substack{j \in M(i) \\ LUT_j \in \{wa,nr\}}} imp_{P}(LUT_j) \tag{F.2}$$

where $imp_P(LUT_j)$ is the impact on productivity of the land use type of neighboring cells j, see Table F.4.

Table F.3: Parameters specifying operations on the cell level.

Parameter	**Symbol**	**Standard value**
Productivity of land use types		
Water bodies	$p_P(wa)$	0
Settlement	$p_P(st)$	0
Nature reserves	$p_P(nr)$	0
Agriculture	$p_P(cr)$	15 +/- 2%
Forest	$p_P(fo)$	5 +/- 2%
Fallow land	$p_P(fa)$	0
Environmental quality of land use types		
Water bodies	$p_{EQ}(wa)$	20 +/- 2%
Settlement	$p_{EQ}(st)$	-15 +/- 2%
Nature reserves	$p_{EQ}(nr)$	10 +/- 2%
Agriculture	$p_{EQ}(cr)$	0
Forest	$p_{EQ}(fo)$	25 +/- 2%
Fallow land	$p_{EQ}(fa)$	5 +/- 2%
Quality of life of land use types		
Water bodies	$p_{QL}(wa)$	0
Settlement	$p_{QL}(st)$	10 +/- 2%
Nature reserves	$p_{QL}(nr)$	0
Agricultural	$p_{QL}(cr)$	0
Forest	$p_{QL}(fo)$	0
Fallow land	$p_{QL}(fa)$	0
Impact land use type as previous use		
Nature reserves / inactive natures reserves	$p_{PU}(nr)$	1
Forest	$p_{PU}(fo)$	0.3
Agriculture	$p_{PU}(cr)$	0
Fallow land	$p_{PU}(fa)$	0.2

We calculate the extended neighborhood impact on the quality of life IQL_i. Here, not only the direct neighbors ($M(i)$) are influential, but also the extended moore neighborhood ($EM(i)$) including the adjacent cells of cell i of order 1 to 3 (i.e., comprising the 48 surrounding cells):

$$IQL_i = \frac{1}{|EM(i)|} \cdot \sum_{\substack{j \in EM(i) \\ LUT_j \in \{st,fo,wa,nr\}}} d_{|i-j|} \cdot imp_{QL}(LUT_j) \tag{F.3}$$

where $imp_{QL}(LUT_j)$ is the impact factor on the quality of life of the land use type of neighbor j (see Table F.4), $d_{|i-j|}$ the distance weighting coefficient based on the appearance in the extended moore neighborhood (see Table F.4), where $|i-j|$ shall shortly summarize, whether j is an adjacent cell of i of the 1st, 2nd or 3rd order. $|EM(i)|$ denotes the size of $EM(i)$.

Table F.4: Parameters for neighboring effects on the cell level.

Parameter	**Symbol**	**Standard value**
Direct neighborhood impact on environmental quality		
nature reserves	$imp_{EQ}(nr)$	0.5
water bodies	$imp_{EQ}(wa)$	1
Direct neighborhood impact on productivity		
nature reserves	$imp_P(nr)$	0.5
water bodies	$imp_P(wa)$	1
Extended neighbourhood impact on quality of life		
water bodies	$imp_{QL}(wa)$	0.1
nature reserves	$imp_{QL}(nr)$	0.1
settlement	$imp_{QL}(st)$	0.5
forests	$imp_{QL}(fo)$	1
Weighting coefficients of distances		
1st order	d_1	1
2nd order	d_2	0.8
3rd order	d_3	0.5

Subsequently, the environmental quality EQ_i, potential productivity P_i, and quality of life QL_i are calculated for each cell. The potential environmental quality of cell i is calculated by:

$$EQ_i = \frac{1}{2} \cdot (SP_i + IEQ_i) \tag{F.4}$$

where SP_i is the site-specific condition and IEQ_i the impact of neighborhood calculated by Equation F.1.

Potential productivity of a cell i is calculated by:

$$P_i = \frac{1}{4} \cdot \left(\frac{1}{10} \cdot EQ_{t-1} + SP_i + IP_i + p_{PU} \cdot LUT_{i,t-1} \right) \tag{F.5}$$

where EQ_{t-1} is the environmental quality on the system level in the previous year (in the initialization phase an initial value for $EQ_{t=0}$ is provided, see Table F.2). In this equation this is the only variable scaled to [0,10] in accordance with all

other state variables. Thus a normalization by 10 is required. SP_i summarizes site-specific conditions (see Table F.1), IP_i the impact of neighborhood calculated by Equation F.2 and the parameter p_{PU} incorporates the impact of the prior use $LUT_{i,t-1}$ on cell i (see Table F.3; in the initialization phase the prior use is set to the current land use type).

Finally, the potential quality of life for cell i is calculated by:

$$QL_i = IQL_i, \tag{F.6}$$

where IQL_i is the impact of the neighborhood calculated by Equation F.3.

These potential characteristics of a cell are not dependent on the current land use type. In the next step, they are therefore combined by the actual land use of cell i. In this step, the indicators environmental quality EQ, productivity AP and quality of life QL on the system level are calculated based on the current landscape (all cells i).

The environmental quality EQ on the system level is calculated by:

$$EQ = \frac{2}{N} \cdot \sum_{i \in L} EQ_i \cdot p_{EQ}(LUT_i) \tag{F.7}$$

where L denotes all cells on the landscape, EQ_i the potential environmental quality of cell i calculated by Equation F.4, $p_{EQ}(LUT_i)$ the site-independent environmental quality of land use type of cell i (Table F.3) and N the total number of cells (see Table F.1). Factor 2 is used to control the level of difficulty in the game (the lower the factor, the more difficult it is to reach the maximal environmental quality which strongly influences the score calculated by Equation F.17).

The indicator productivity AP on the system level is calculated by:

$$AP = \frac{3}{N} \cdot \sum_{\substack{i \in L \\ LUT_i = cr}} P_i \cdot p_P(cr) \tag{F.8}$$

where L denotes all cells on the landscape, P_i is the potential productivity of cell i calculated by Equation F.5, $p_P(cr)$ the site-independent productivity of agricultural land (see Table F.3) and N the total number of cells (see Table F.1). Again, factor 3 is used to control the level of difficulty in the game (see above).

Finally, quality of life QL on the system level is calculated by:

$$QL = \frac{1}{N_{st}} \cdot \sum_{\substack{i \in L \\ LUT_i = st}} QL_i \cdot p_{QL}(st) \tag{F.9}$$

where L denotes all cells on the landscape, QL_i the potential quality of life of cell i calculated by Equation F.6, $p_{QL}(st)$ is the site-independent quality of life of settlement areas (Table F.3) and N_{st} the total number of settlement cells (see Table F.1).

All remaining indicators are set to the initial values given in Table F.2. The needs are then calculated based on the indicators population and consumption:

$$Nd = \sqrt{Pop \cdot Con} \tag{F.10}$$

where Pop is the current population and Con the consumption. The square root is taken to receive values between 0 and 10 and to additionally diminish additional increase in needs, when there is already high population or consumption.

Finally, the current market price for agricultural products Pr is determined by:

$$Pr = \min\left(\frac{Nd \cdot pf_{ag}}{\max(AP,1)}, pr_{max,ag}\right) \tag{F.11}$$

where Nd are the current needs, AP the total productivity according to Equation F.8, pf_{ag} a weighting factor for the market price and $pr_{max,ag}$ the maximal market price, see Table F.5.

F.7.2 *Player's action: choosing investments for land use and education*

The player can invest its financial resources in the five different policy options:

- Agricultural investments ID_{AP}
- Settlement policy ID_{SeP}
- Afforestation measures ID_{AF}
- Investment in nature conservation ID_{NC}
- Investment in education ID_{Ed}

Investment in nature conservation (ID_{NC}) is measured in percent change of nature reserves in the landscape. At this, one percentage costs three money units and change is restricted to 10% percent per time step. The four other policy options are only constrained by the availability of financial resources. Investment in settlement policy (ID_{SeP}) changes the maximal population capacity of the settlement cells. Investment in agricultural production (ID_{AP}) and afforestation measures (ID_{AF}) impacts the profit of agricultural production and forestry, respectively. Finally, investment in education (ID_{Ed}) impacts the indicator education. In this step, however, the different heights of invested money units are only recorded and will be used in the following sections. See Figure F.2 for translation of investments in changes of model parameters or indicators.

Table F.5: Economic parameters on the system level.

Parameter	**Symbol**	**Standard values**
Financial resources		
Weighting coefficient for capital from agricultural production	fac_{ag}	3
Weighting coefficient for capital from forestry	fac_{fo}	1
Weighting coefficient for overall capital	fac	1.5
Market		
Weighting coefficient of price for agricultural products	pf_{ag}	10
Maximal price for agricultural products	$pr_{max,ag}$	20
Price for forest products	pr_{fo}	5
Weighting coefficient of price for forest products	pf_{fo}	1
Transformation costs		
cr $\rightarrow$ fa	$tc_{cr\rightarrow fa}$	0
cr $\rightarrow$ fo	$tc_{cr\rightarrow fo}$	1.2
cr $\rightarrow$ cr	$tc_{cr\rightarrow cr}$	0.4
fa $\rightarrow$ cr	$tc_{fa\rightarrow cr}$	2.7
fa $\rightarrow$ fo	$tc_{fa\rightarrow fo}$	1.8
fo $\rightarrow$ cr	$tc_{fo\rightarrow cr}$	2.4
fo $\rightarrow$ fa	$tc_{fo\rightarrow fa}$	0
fo $\rightarrow$ fo	$tc_{fo\rightarrow fo}$	0
inr $\rightarrow$ cr	$tc_{inr\rightarrow cr}$	2.7
inr $\rightarrow$ fo	$tc_{inr\rightarrow fo}$	1.7

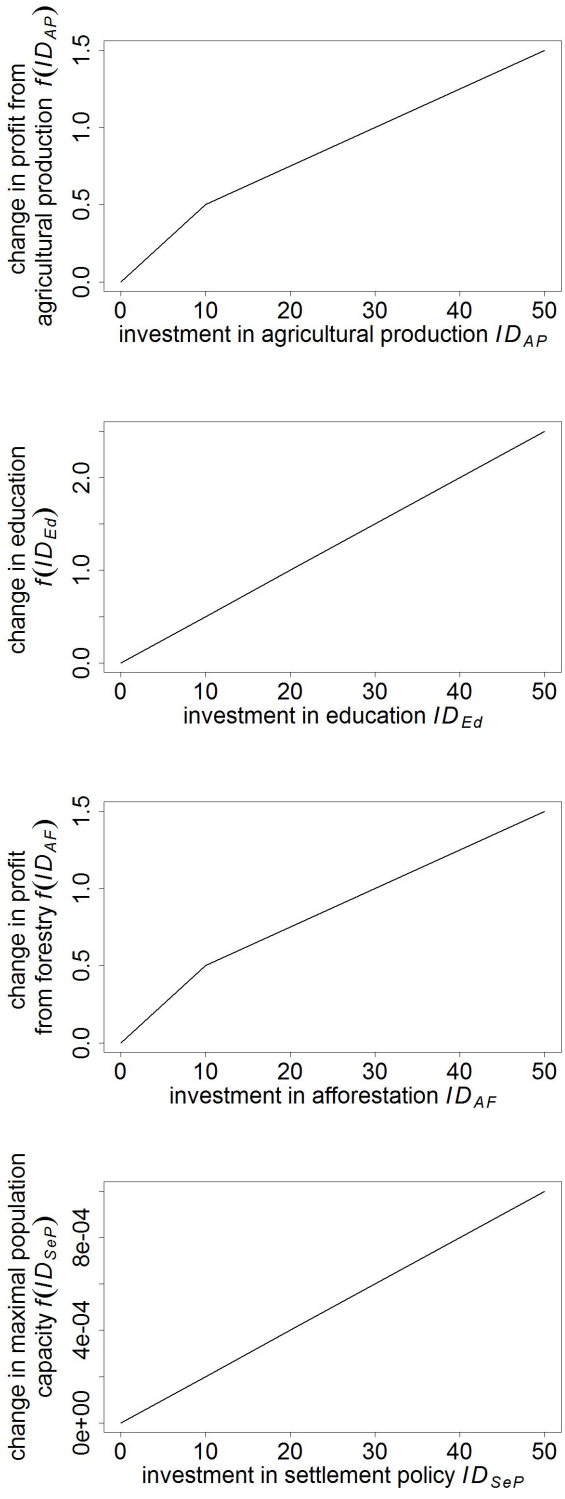

Figure F.2: Conversion of investment decisions.

F.7.3 *Consequences of player's action*

Land use change is primarily driven by the investment decisions of the player, but also by the market and the current population size.

1. Areas of nature reserves are decreased or increased based on a chosen percentage by the player. At this, the potential environmental quality of the areas determines which cells are to be changed. Based on the chosen percent change the number of nature reserves that has to be added or discarded is determined.

   - To increase the number of nature reserves, the potential environmental quality of all cells under question (i.e., agricultural production, fallow land, forest and inactive nature reserves) is determined (see Equation F.4). Those cells with the highest potential environmental quality become nature reserves.
   - If the number of nature reserves is to be decreased, the potential environmental quality of all nature reserves cells is determined and those with the lowest potential environmental quality are changed to inactive nature reserves.

   After the allocation of additional nature reserves the potential quality of life on the cell level is updated by Equation F.6, which requires recalculation of Equation F.3 before further changes in the landscape are simulated.

2. Investment in settlement policy determines the maximal population capacity $PC_{max,i}$ of the cells. Higher investment more strongly raises the capacity (see Figure F.2). Based on the updated capacity and the current population size we calculate the number of necessary additional settlement cells. If so, the potential quality of life QL_i of the possible cells (i.e., agricultural production, fallow land, inactive nature reserves and forest) is determined and the ones with the highest change to settlement.

3. After the allocation of additional settlements the following characteristic on the cell level are updated before further changes in the landscape are simulated: potential environmental quality, potential productivity and potential quality of life (by Equations F.4, F.5, F.6 requiring recalculation of Equations F.1, F.2, F.3, respectively).

4. For all remaining cells (i.e., agricultural production, fallow land, forest and inactive nature reserves), we calculate the profit for agricultural production and forestry by Equations F.12 and F.13, respectively.

$$Profit_{ag,i} = Pr \cdot P_i + f(ID_{AP}) - tc_{LUT_i \to cr} \tag{F.12}$$

where Pr is the market price for agricultural products calculated by Equation F.11, P_i the potential productivity of cell i calculated by Equation F.5, $tc_{LUT_i \to cr}$ the transformation costs from current land use to agricultural production (see Table F.5) and $f(ID_{AP})$ the profit change due to investment of the player in agricultural production (see Figure F.2).

$$Profit_{fo,i} = pr_{fo} \cdot P_i + f(ID_{AF}) - tc_{LUT_i \to fo} \tag{F.13}$$

where pr_{fo} is the current market price for forest products, P_i the potential productivity of cell i calculated by Equation F.5, $tc_{LUT_i \to fo}$ the transformation costs from current land use to forest (see Table F.5) and $f(ID_{AF})$ the profit change due investment of the player in afforestation measures (see Figure F.2).

The land use option with the higher profit is chosen. If both profits are negative, the land will change to fallow land (unless it's an inactive nature reserve, those will stay the same). As land use changes regarding the land use type forest influence the quality of life of cells through neighboring effects, the potential quality of life QL_i on the cell level is updated by Equation F.6, which requires recalculation of Equation F.3.

5. Investments in education directly influence the indicator education Ed. Here, according to the money units invested by the player, the value of indicator education is updated (see Figure F.2).

F.7.4 *Calculation of indicators based on landscape*

After updating the landscape, we calculate those indicators that are directly influenced by the landscape: environmental quality, agricultural production and quality of life by Equations F.7, F.8, F.9.

F.7.5 *Indicator feedbacks, external effects and market dynamics*

In this step, indicators are updated based on a set of functional relationships between the indicators (see Figure F.3). This is done synchronously, i.e., indicators are updated not until all indicators have been calculated. This updating concerns the following indicators: education Ed, quality of life QL, environmental quality EQ, population Pop and consumption Con. The calculation of needs of the current time step (see Equation F.10) is then determined by the updated values of consumption and population.

The feedbacks between various indicators are calculated by nonlinear functions, which are coded in accordance with findings from recent literature. For instance, environmental quality and quality of life are positively correlated (see Figure F.3). A

minor deterioration of an already catastrophic state of the environment has a strong negative impact on the quality of life, while the effect of a marginal improvement is only slightly positive (Hassan et al., 2005). Additionally, a high educational level decreases consumption, the degree at which average people use products in the country, since they are more aware of negative consequences. However, the decrease is small because people tend to act in favor of individual needs and information does not necessarily change their behavior (Abrahamse et al., 2005). Education also strongly influences development of the population (see Figure F.3). Here, a higher level of education decreases the population growth (Lutz and KC, 2011).

Furthermore, the level of education effects the quality of life as higher educational level enables people to follow individual plans. The level of education is influenced by the state of the environment. Severe environmental conditions generate awareness and engagement in improvements of the environmental quality.

Between the indicators population and quality of life exists a mutual relationship. High as well as low population size negatively influence quality of life. Overpopulation leads to insufficient job opportunities, while underpopulation leads to unattractive vacancies in cities. On the other side, high as well as low quality of life decrease population size. For low quality of life, bad health conditions increase death rate and decrease birth rate. High standard of living and the desire to sustain it also lead to lower birth rate.

Some indicators show self-influencing mechanisms. Environmental quality influences itself as for medium levels of environmental quality self-regulation takes place. Furthermore, self-regulation takes place in population dynamics. The larger the population, the more it growths. However, for small population growth also increases in order to avoid population extinction in the game. Education is constantly decreased each year due to ongoing costs.

Finally, financial resources effect the quality of life. Low financial reserves negatively influence the quality of life as people feel insecure. A stable economy increases the quality of life. However, for high national budgets a saturation occurs.

After all indicators have been calculated, possible external effects, e.g., trade with regions outside the governed country are taken into account by computing surplus or lack of agricultural products, which then determines possible export or import:

$$Tr = AP - Nd \tag{F.14}$$

where AP is the agricultural production and Nd the current needs of the population, see Equations F.8 and F.10.

Subsequently, the market price is calculated based on the current needs and agricultural production by Equation F.11. Possible deviation to this regional market price due to global effects is determined. In three out of ten years, which are randomly chosen, the market price is randomly increased or decreased by up to 100%. Hereby, sudden changes in global markets and their impact on the national economy are incorporated into the game.

Financial resources of the player for the next year are calculated. Besides income from agricultural production, forests are also assumed to generate income:

$$FR_{fo} = pr_{fo} \cdot \sum_{\substack{i \in L \\ LUT_i \in \{fo\}}} \frac{P_i \cdot p_P(fo)}{\frac{1}{10} \cdot N} \tag{F.15}$$

where L denotes all cells on the landscape, P_i the potential productivity of cell i calculated by Equation F.5, $p_P(fo)$ the standard productivity of land use type forest (see Table F.3) and N the total number of cells (see Table F.1) . Finally, the financial resources are calculated by:

$$FR_t = \frac{FR_{t-1} + Nd \cdot Pr \cdot fac_{ag} + Tr \cdot Pr \cdot fac_{ag} + FR_{fo} \cdot fac_{fo}}{fac} \tag{F.16}$$

where FR_{t-1} are the financial resources from the previous year, Nd are the current needs calculated by Equation F.10, Pr the market price for agricultural products calculated by Equation F.11, Tr is the amount of imported/exported goods (negative or positive value respectively) calculated by Equation F.14, FR_{fo} the income generated from forestry as calculated by Equation F.15, fac_{ag} a factor weighting the capital from agricultural production, fac_{fo} a factor weighting the capital from forestry, and fac a weighting factor for the overall capital (see Table F.5).

Finally, the indicator quality of life is updated once more based on the financial resources (see Figure F.3).

F.7.6 *Calculation of score*

At the end of each step, we check whether exit conditions occur (i.e., time step 10 completed; minimal quality of life or environmental quality) or additional bonus points are obtained (i.e., maximal quality of life and environmental quality). Finally, the score S is updated by:

$$S_t = S_{t-1} + QL + EQ + \frac{1}{20} \cdot FR + bonus \tag{F.17}$$

where S_{t-1} is the score from the previous year, QL the quality of life, EQ the environmental quality, FR the financial resources and $bonus$ possibly obtained bonus points.

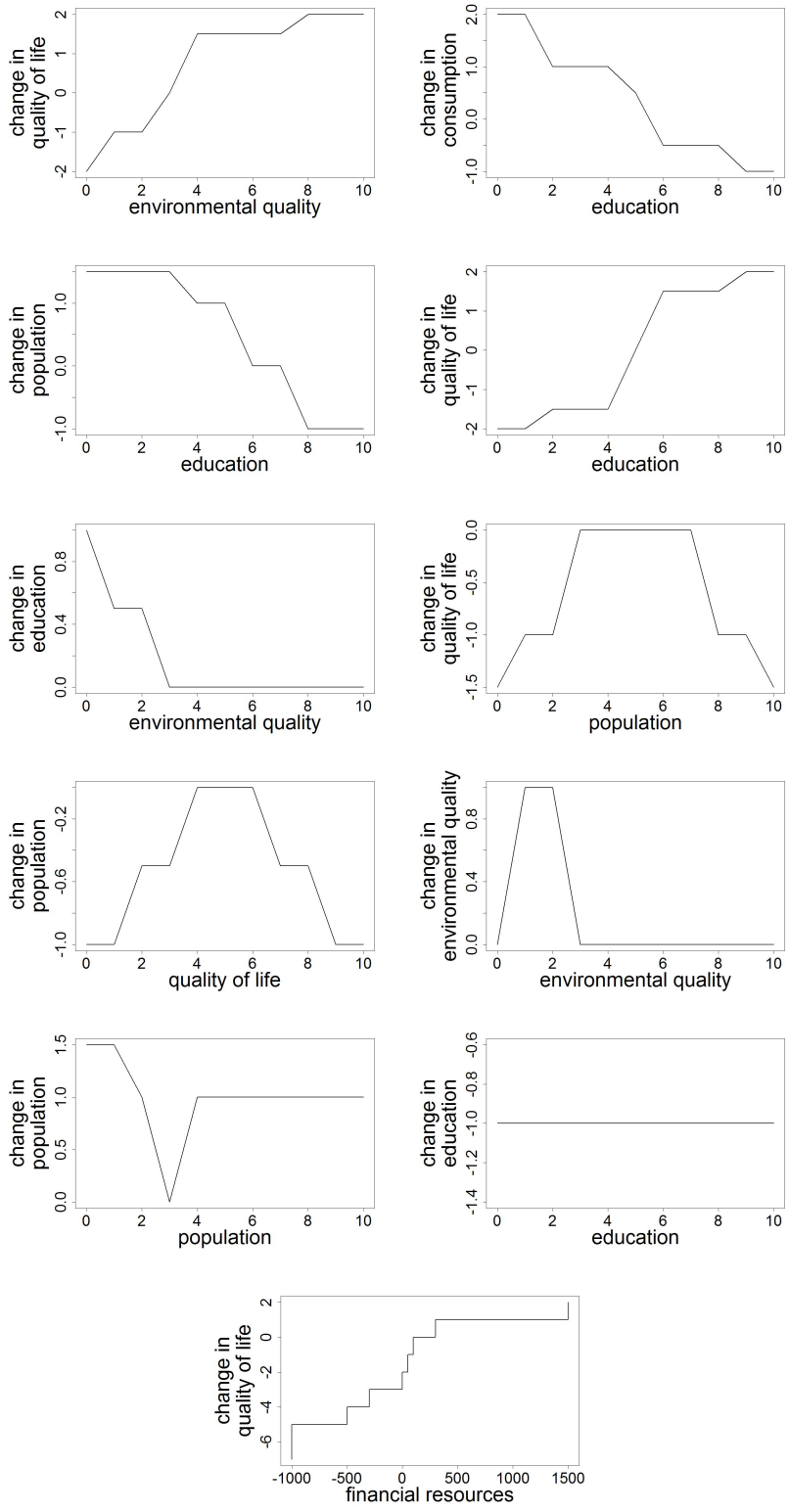

Figure F.3: Aggregated relationships between the indicators.

F.8 REQUIRED UPDATES

Table F.6: Envisioned, planned and required updates. Priorities denote $\mathcal{A}$: important and as soon as resources are available, $\mathcal{B}$: important but not as urgent as $\mathcal{A}$ and $\mathcal{C}$: optional and nice to have.

No.	Description	Priority
1	Revisit Equation F.16 and check parameters setting for economy, revise update of global market	$\mathcal{A}$
2	Add balance sheet in each round for information on investments and their effects	$\mathcal{A}$
3	Revisit feedback "education-consumption" and include negative relationship as alternative scenario to choose from	$\mathcal{B}$
4	Make parameters that control difficulty or the game explicit and provide selection of level-of-difficulty to the online game	$\mathcal{B}$
5	Language addition (Russian, Czech)	$\mathcal{B}$
6	Different level of complexity (for instance deactivate global markets)	$\mathcal{B}$
7	Different initial conditions referring to different countries	$\mathcal{C}$
8	Multi-player mode: negotiating global markets by multiple players	$\mathcal{C}$

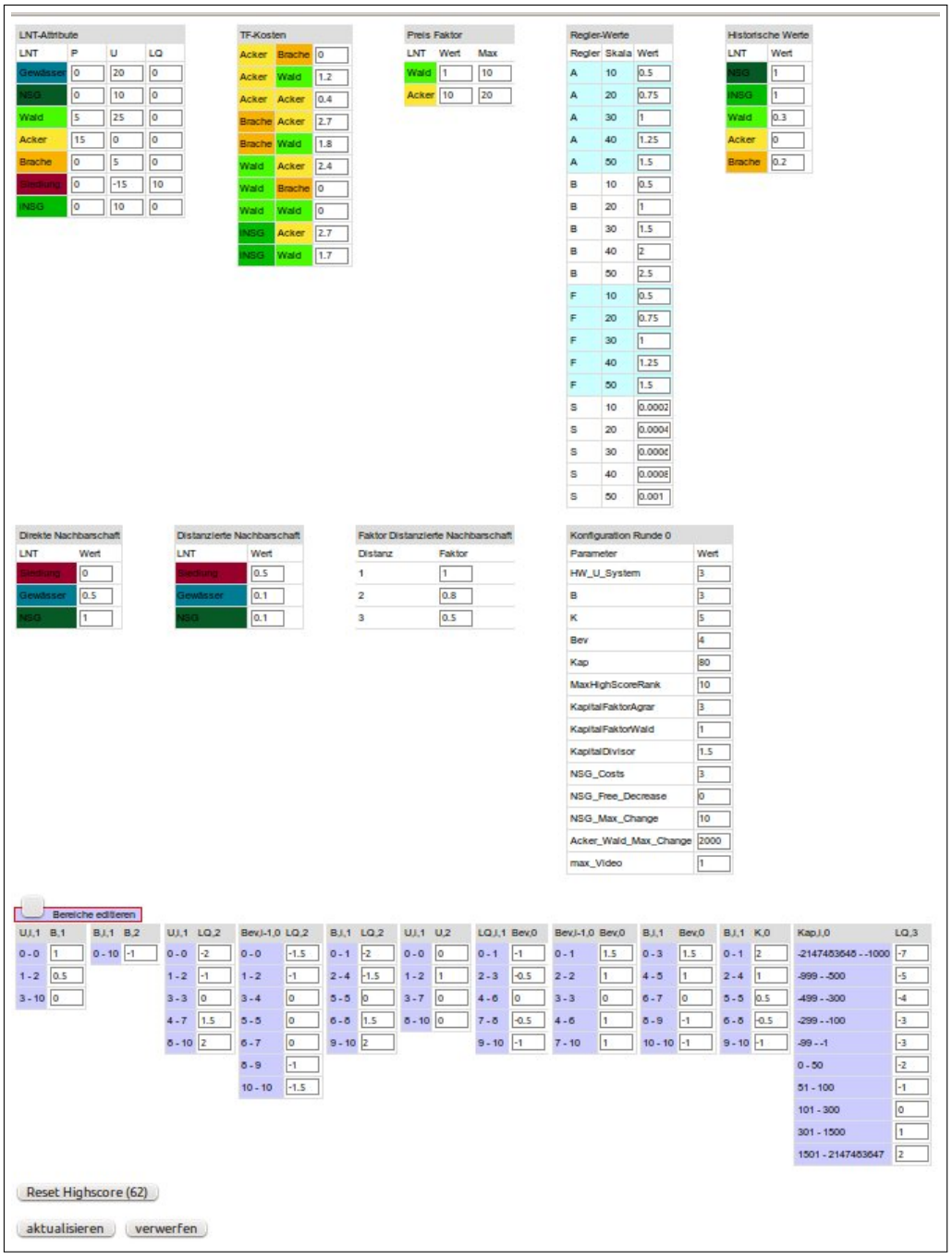

Figure F.4: Model interface (Back-End). Possible Modification here refer to: upper row: (i) Productivity of land use types $p_P(LUT)$, environmental quality of land use type $p_{EQ}(LUT)$ and quality of life of land use type $p_{QL}(LUT)$; (ii) transformation costs tc, (iii) market parameters, (iv) conversion of investment decisions, (v) impact of prior use $p_{PU}(LUT)$; center row: (vi) neighborhood impact, (vii) weighting coefficients of distances, (viii) initial conditions; and bottom row: (ix) specification of feedback functions and (x) resetting the high score list.

G

APPENDIX 2 OF CHAPTER 5

This appendix contains the online survey to test the serious game LandYOUs presented in Chapter 5 of this thesis. It is listed as supplementary material for the publication: Schulze, J., Martin, R., Finger, A., Henzen, C., Lindner, M., Pietzsch, K., Werntze, A., Zander, U., Seppelt, R. (2015). Design, implementation and test of a serious online game for exploring complex relationships of sustainable land management and human well-being. Environmental Modelling and Software 65, 58-66.

Dear respondent,

Thank you for taking the time to complete this online survey. Our survey is anonymous and the gathered information will help us to improve the current working version of our game. Your opinion is very important to us, therefore we ask you to answer the questions honestly and completely. Your survey responses will be used only for the specified purposes and not shared with third parties. Thank you for your support of the project!

Some questions can be answered by selecting one of the offered options.

1. How many times have you played the game before completing this questionnaire? [number] times
2. Statements (listed in table):
    - I often play computer games in my free time.
    - I am well informed about land use and land use change.
    - I think the simulation is based on objective scientific knowledge.
    - I think the simulation is based on personal opinions and attitudes of the developers.
    - I am satisfied with my performance during the game.
    - I was excited playing the game.
    - During the game I was able to act as I wanted.

- I consider the game very interesting.
- While playing the game I felt under pressure.
- I think I was playing pretty well.
- I had a lot of control over the game.

Answers options (1 out of 5) [Strongly agree - Agree - Neither agree or disagree - Disagree - Strongly disagree]

3. Statements (listed in table)
   - The game was entertaining.
   - While playing the game I was able to freely decide.
   - While playing the game I proofed to be a clever player.
   - I was concerned whether I would be able to handle the game.
   - I had fun playing the game.
   - The text color makes reading pleasant.
   - The font sizes used in the game were appropriate.
   - The functions of the individual buttons were clear and apparent.
   - The color scheme helps to operate the game.
   - The information in the charts was easy to understand.

   Answers option (1 out of 6) [Strongly agree - Agree - Neither agree or disagree - Disagree - Strongly disagree]

4. Do you have any specific comments towards the user-friendliness of the program? [free text]

5. The following elements have helped me while playing the game (listed in table)
   - Tutorial
   - Information at the sliders / scroll bars
   - Text in the result image at the end of the round
   - Graphic changes of the result image at the end of the round
   - Map

   Answers options (1 out of 6) [Strongly agree - Agree - Neither agree or disagree - Disagree - Strongly disagree]

6. The following elements have helped me to make the investment decisions (listed in table)
   - Diagram areas (education, consumption, etc.)

- World market price chart
- Investment chart
- Import/Export chart
- Legend information next to map

Answers option (1 out of 6) [Strongly agree - Agree - Neither agree or disagree - Disagree - Strongly disagree]

7. Instead of the current tutorial I would prefer one test game round. [Yes - No]
8. What is your opinion about the existing tutorial? [free text]
9. What factors in the game affect the amount of the available capital? [free text]
10. What factors influence the high score? [free text]
11. In your opinion, what are the goals of the game? [free text]
12. What did you like the most about the game? [free text]
13. What did you dislike about the game? [free text]
14. Age [number] years
15. Gender [Male - Female]

H

APPENDIX 3 OF CHAPTER 5

This appendix contains the explanation of the short version of the intrinsic motivation inventory concept used in Chapter 5 of this thesis. It is listed as supplementary material for the publication: Schulze, J., Martin, R., Finger, A., Henzen, C., Lindner, M., Pietzsch, K., Werntze, A., Zander, U., Seppelt, R. (2015). Design, implementation and test of a serious online game for exploring complex relationships of sustainable land management and human well-being. Environmental Modelling and Software 65, 58-66.

In psychology, interest and motivation are two closely interlinked concepts. Interest is defined as a tendency of a learner to repeatedly confront himself with the subject of interest in a joyful manner and without external provocation (Krapp, 2005). Two basic concepts exist. In the first, interest is considered an individual disposition of a learner and is relatively stable in lifespan. In the second, interest can also be related to the situation. This is called situated interest, which is influenced by the learning situation and the objects. Krapp (2005) assumes that situated interest is often a beginning of a longer-term development, which ultimately can result in individual interest. In the process of interest development, the intrinsic motivation plays a key role. Thus, a high intrinsic motivation has a positive effect on the interest development. Deci and Ryan (1993) introduced the self-determination theory, which allows evaluating intrinsic motivation by using the Intrinsic Motivation Inventory (IMI). Deci and Ryan (1993) claim that the intrinsic motivation is essentially influenced by three basic needs ("autonomy", "competence" and "relatedness"). A high intrinsic motivation can be assumed if these three basic needs are fulfilled.

LIST OF FIGURES

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