Land use change in the context of bioenergy production: Impact assessment using agent-based modeling

Dissertation zur Erlangung des Doktorgrades der Naturwissenschaften (Dr. rer. nat.) am Fachbereich Mathematik/Informatik der Universität Osnabrück

vorgelegt von Hanna Weise aus Husum

Osnabrück 2013

For my parents and my grandparents.

"Das Bauen mit belebten Steinen
ist eine höchst verzwickte Sache."

Wilhelm Busch

Abstract

Bioenergy is seen as a solution to multiple topical challenges (i.e. an increasing energy demand, scarcity of fossil fuels, climate change). Therefore it is extensively politically fostered in many countries. One effect of this fostering is land use change which can have numerous unintended ecological and social side-effects. Examples include increasing carbon dioxide emissions through the destruction of terrestrial carbon stocks (e.g. when deforestation takes place) or the reduction of food supplies when land users switch to bioenergy production.

This doctoral thesis investigates the land use change that is triggered through an increasing bioenergy demand. This is done with the method of agent-based modeling (ABM). In Part I of this study we present a stylized ABM that comprises markets and policy instruments as drivers of land use change. In Part II we apply the model to investigate the impact of an increasing bioenergy demand in the land use system. We evaluate the changing land use patterns from the perspective of climate change mitigation. We are able to characterize technological, ecological and economic framework conditions that will likely lead to unwanted side-effects. In addition, we ask whether regionally optimized policy instruments can enable sustainable bioenergy production. Our model allows the comparison of differently designed instruments. We show that specific designs of policy instruments are effective to mitigate the unwanted side effects on the climate. However, their application leads to the occurrence of a new socio-economic side-effect.

Part III of this thesis is dedicated to further methodological development of the ABM method. The potential of ABMs is often hampered by a lack of transparent model descriptions. We address this issue by the provision of a standardized protocol that is adapted for the description of human decisions. It is an extension of the widely-used ODD protocol which adds questions for informations that were found to be missing for the understanding of ABMs in a literature survey. We further present an overview of existent techniques of model descriptions in ABM and evaluate their suitability to address different purposes.

Overall, this thesis contributes to an improved understanding of the impact of a bioenergy demand as a new driver of land use change. The results allow to disentangle the effects of economic, ecological and technological framework conditions on the impact of bioenergy and to evaluate policy options to counteract unwanted side effects.

Contents

1. Introduction

1.1. The bioenergy issue

The basic concept of bioenergy utilization is to substitute energy from fossil or nuclear sources by bioenergy, which can be defined as "all energy that is produced from biological mass that is available on a renewable basis (either used directly or as byproducts or waste)" (Don et al., 2012). While the concept and the definition are rather straightforward, many other aspects of the topic are complex.

To begin with, bioenergy utilization has been hailed as a solution to multiple topical key challenges. It was seen as a promising means to reach the strategic goals of security of energy supplies, independence from fossil fuels, climate change mitigation and the additional generation of value in rural areas (Plieninger et al., 2006, WBGU, 2009, Gamborg et al., 2012). Bioenergy has the potential to contribute significantly to the worlds primary energy supply (WBGU, 2009, Chum et al., 2011, GEA, 2012). In addition, population and economic growth cause an increase of the energy demand (Edenhofer et al., 2011, Smith et al., 2013) and fossil energy carriers (which are currently primarily used to meet the demand) are not renewable. In contrast, bioenergy feedstocks are renewable and have the advantage to be storable (unlike energy from wind or solar power).

The potential of bioenergy is particularly of interest, because a consensus exists among many nations that human induced climate change needs to be mitigated (UNFCCC, 2013). The energy sector and transportation contribute to a large extent to climate change (IPCC, 2007), being potential areas of application for bioenergy at the same time. Climate change mitigation through bioenergy utilization is possible, although not to the extent that was assumed when policies to foster bioenergy were introduced (Searchinger, 2010, Haberl, 2013).

As a consequence of these advantages many countries installed policies to foster bioenergy (overviews can be found in WBGU, 2009, Sorda et al., 2010). The diversity of the strategic goals of bioenergy production is partly reflected in the fact that the policies apply to various sectors (e.g. the agrarian and the energy sector, Witcover et al., 2013). A particularly influential example of a policy to foster bioenergy is the EU renewables directive (RED, 2009), which includes blending mandates for transportation fuels. Policies that set this kind of supply targets create a demand for crops that can be used as bioenergy. The demand appears at markets and leads to price incentives for land users. They may react by changing their land use to bioenergy production. This can cause the replacement of other forms of land use (WBGU, 2009). The land use forms that may be replaced can be food production or natural areas, like forests or grasslands (Fargione et al., 2008, FAO, 2009, Lapola et al., 2010).

This land use change has ecological as well as socio-economic consequences which may be adverse. Examples for negative ecological effects include the loss of biodiversity (e.g. Eggers et al., 2009, Engel et al., 2012), water pollution through fertilizers and pesticides (e.g. Lautenbach et al., 2013) or greenhouse gas emissions through land use change (e.g. Searchinger et al., 2008, Fargione et al., 2008, Lange, 2011, Smith and Searchinger, 2012).
The most prominent example for an unwanted socio-economic effect are increasing food prices because of a shortage of supply of agricultural commodities. While the extent of the influence of bioenergy on recent food price hikes is contested, it is acknowledged that bioenergy is a factor (FAO, 2008, 2009). Hence, the coupling of agricultural and energy markets through bioenergy remains a concern for food security (WBGU, 2009). These negative side effects can put the achievement of the strategic goals of bioenergy utilization at stake.

To add to the complexity, there is a variety of bioenergy feedstocks, ranging from dedicated energy crops to side products and waste. These can be converted in a plethora of bioenergy pathways leading to different forms of secondary and final energy (WBGU, 2009, Chum et al., 2011). Many of these pathways differ in terms of their environmental impacts (for impact assessments of different pathways see Adler et al., 2007, Cherubini et al., 2009, Sterner and Fritsche, 2011).

To conclude, fostering bioenergy is an attractive option to react to multiple challenges. However, it may cause land use change with potentially harmful consequences (i.e. unwanted side effects).
Three questions emerge from these observations. The first is: what is the impact of the introduction of a bioenergy demand in the land use system? The second (related) question is: how are effects on the land use system linked to the occurrence of unwanted side effects? A third question, given the multiple advantages of bioenergy, is: Can unwanted side effects be mitigated by an appropriate policy response?
Our approach to answer these questions is to design and analyze a stylized agent-based model of the bioenergy issue.

1.2. Land use modeling in the context of the bioenergy issue

Many land use models that deal with the bioenergy issue have the purpose to model the potential of bioenergy production, respectively the potential of bioenergy to contribute to the global energy supply (for an overview see Chum et al., 2011). Sustainability considerations (i.e. the avoidance of unwanted side effects) are often modeled in the form of constraints regarding the areas that are considered for bioenergy production. The

constraints are usually derived from scenarios concerning various social or ecological goals of sustainability, e.g. the meeting of a specific food demand or the conservation of areas with a high significance for biodiversity (examples can be found in WBGU, 2009, Lotze-Campen et al., 2010, Haberl et al., 2011, Erb et al., 2012, Gelfand et al., 2013).
These models can provide detailed options for sustainable bioenergy production. However, it is out of their scope to analyze under which conditions unwanted side effects emerge and to test how the respective sustainability goals can be achieved.

Another group of models deals with the impact analysis of different scenarios of bioenergy production. They often focus on the risks of unwanted side effects. Examples include studies of increasing greenhouse gas emissions (e.g. Searchinger et al., 2008, Lapola et al., 2010), loss of biodiversity (e.g. Engel et al., 2012, Stoms et al., 2012) or water pollution (e.g. Lautenbach et al., 2013) through bioenergy production. These models can give useful information about the consequences of a specific bioenergy policy on the impact of interest. However, other drivers of land use change in their interplay are not accounted for. Furthermore, although they often provide suggestions for management options to counteract unwanted effects, the evaluation of these in the presence of multiple drivers is out of scope.

So far, there are no modeling approaches that evaluate the bioenergy issue from a systemic perspective, taking into consideration the strategic goals of bioenergy production, the different drivers of land use change, the ways in which these lead to multiple effects and the functioning of possible policy responses to unwanted side effects. Therefore our goal is to contribute to system understanding with a modeling framework that is suited to study the bioenergy issue along the whole "Driver-Pressure-State-Impact-Response Chain" (Smeets et al., 1999).

1.3. Our aim - system understanding through a stylized agent-based model

Figure 1.1 shows a representation of the bioenergy issue in terms of drivers, pressures, impacts and responses. The political fostering of bioenergy leads to an increasing bioenergy demand. This demand occurs at the markets and acts as a driver of land use change. It does so because land use decisions are influenced by changing incentives from markets and by policies (Geist and Lambin, 2002, Turner et al., 2007). This pressure leads to land use change, which then causes the intended and unintended impacts of bioenergy in different fields. Note that the impacts that are shown in figure 1.1 are only examples for possible evaluation options of land use patterns. If unwanted impacts occur, policy instruments can be employed as a response to influence the land use decision.

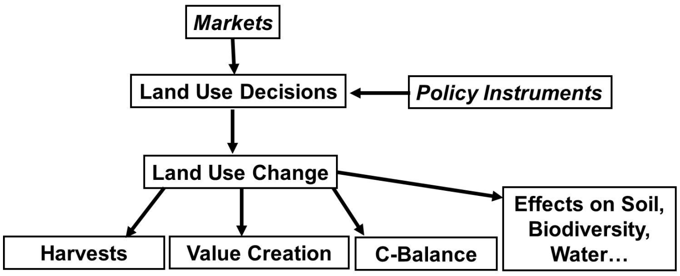

Figure 1.1.: Schematic overview of the bioenergy issue in terms of drivers, pressure, impact and response.

These considerations show that the land use decision is a central process for two reasons. Firstly, it links policies that foster bioenergy to their multiple effects. Secondly, when policy instruments are used as a response to unwanted impacts of bioenergy production, they apply at this location in the system.

Therefore, we have to model the land use decision explicitly in the simulation model that is derived from this conceptual model. Hence, we chose to design it as an agent-based model (ABM). This type of model is particularly well suited to represent the results of individual decisions and is widely used to analyze problems in the context of land use change (overviews are given in Matthews et al. (2007), Hare and Deadman (2004), Parker et al. (2003, 2008b), Rounsevell and Arneth (2011).
ABMs are also well suited to model the coupling of social and ecological systems (Parker et al., 2008b, Janssen and Ostrom, 2006b, Filatova et al., 2011). This is advantageous for an integrated impact analysis of the effects of bioenergy production.

So far, two agent-based models have been developed to study the bioenergy issue: The focus of the model of Klassert et al. (2013) is on transregional land use dynamics through bioenergy policies. Its purpose is to describe the impacts of policy instruments in one region on land use change and its ecological and economic impacts in a connected region.
Scheffran (2007) and Scheffran and BenDor (2009) study the change of land use patterns in response to increasing demands for energy crops. Their studies do not provide an impact analyses beyond changes in harvests respectively land cover.

Another design choice that we made is the use of a stylized model. This kind of model is primarily helpful to create an artificial world which can be utilized as a tool to assist thinking. Examples for stylized models from land use research can be found in Parker and Filatova (2008) and Filatova et al. (2011). The main purpose of stylized models is to generate hypotheses. Stylized models can also serve to illustrate the consequences of choosing certain courses of action. The high degree of abstraction fosters their communicableness. This can spark lively debates (e.g. the discourse on the World2 and World3 model, cited in Bardi, 2011). One of our goals is to compare policy options which makes this feature desirable.

Stylized models are characterized by a high level of abstraction and highly aggregate variables. Therefore the number of variables is smaller than in models that are closer to reality. This leads to better tractability, which is useful, because we want to contribute to system understanding. Further, stylized models can be an important first step towards more realistic models by pointing out important factors or processes. This suits the modular design of our modeling framework which allows for a stepwise extension towards more realistic models.

1.4. Outline of the thesis

This thesis consists of four parts. In Part I we describe the stylized, agent-based model that we developed (see Chapter 2). The aim of Chapter 3 is to introduce and to explain the model dynamics with an emphasis on the understanding of the model‘s market mechanism.
In Part II we will use the model for the analysis of questions from the bioenergy context. It consists of two chapters. The goal of Chapter 4 is to understand the effect of an increasing bioenergy demand on the land use system. We focus on carbon balances in our impact analysis, because this is an interesting example for a goal conflict of bioenergy production. In Chapter 5 we built upon the previous chapter by choosing a case where bioenergy production has a detrimental effect on the climate. We then test the potential of differently designed policy instruments to counteract this side effect.
Part III differs in several aspects from the previous parts. Firstly, it does not deal with the bioenergy issue, but has a methodological focus concerning the advancement of agent-based modeling. Secondly, it contains one published and one submitted manuscript which originated from the work of a journal club (that was co-coordinated by me). Therefore Chapters 6 and 7 contain the results of a team effort.
In Chapter 6 we present a protocol for the description of agent-based models. It is an extension of the widely used ODD protocol (Grimm et al., 2006, 2010) with a focus on the description of human decisions. We use the protocol in our model description in Chapter 2. The other chapter of Part III (Chapter 7) concerns the advancement of the communication of agent-based models. It is an opinion paper that originated from a conference workshop. Different established methods to communicate ABMs to various audiences are described and their advantages and disadvantages are discussed in this paper.
In Part IV we discuss and synthesize our results.

Part I.

Introducing an agent-based model to analyze land use change in the context of bioenergy production

2. Modeling framework

2.1. Introduction

In this chapter we describe the modeling framework that we developed and used for the studies in Part II of this thesis. We apply a novel method of description for agent-based models, the ODD+D protocol (Müller et al., 2013). It was developed as a part of this thesis in a team effort with other scientists from the Helmholtz Centre for Environmental Research. The protocol is an extension of the widely used ODD-protocol (Grimm et al., 2006, 2010). The goal is to enable the transparent model description of human decisions in agent-based models. Further details of the protocol and its development can be found in Chapter 6.

2.2. Model Description in ODD + D

I Overview

I.i Purpose

The purpose of the model is to understand the interplay of different drivers of land use change and land use decisions in the context of the bioenergy issue. The drivers that we study are market demands and political goals which are implemented by various policy instruments. Both drivers influence land use decisions. This leads to the emergence of specific land use patterns which are evaluated from multiple perspectives (e.g. climate balances, total harvests).
The model is a stylized model with the main objective of system understanding. It is designed in a modular way (i.e. comprising an agent decision model, a market model etc.). The purpose of this design is to be able to gain system understanding by contrasting results from the reference version of the model with model versions with exchanged modules. The model version that is presented here is the reference case, against which model versions with extended complexity can be tested. The model is written for a scientific audience, because the purpose is system understanding.

I.ii Entities, state variables and scales

Figure 2.1 shows an overview of the model‘s entities. The model consists of one type of human agents and of spatial entities. The human agents are land users. The spatial entities (cells) are areas that can be used for agricultural production. The model further comprises institutions. These are a market for energy crops, a market for other agrarian products and policy instruments.

An overview of the model parameters and state variables can be found in Tables 2.1 and 2.2.
The land-user agents are characterized by an identity number.They decide on the land use of their cell for either the production of other agricultural commodities, the production of energy crops or no cultivation, respectively fallow land.Their decision model is *Homo oeconomicus*. Each agent has a cost function, consisting of production costs and a cost term for changing production.

The spatial entities have an identity number that is equivalent to the number of the agent who owns the cell. They are further characterized by the land use on them. The spatial entities are homogeneous as well, because all of them have the same size and the same quality for production.
We are interested in the climate effect of the land use pattern (among other evaluation criteria). Therefore, the carbon dynamic (C-dynamic) of each cell is modeled explicitly. Each cell is characterized by its current C-stock as a state variable. The cells have a minimum and a maximum C-stock and a maximum C-sequestration rate.
The institutional entities are markets and policy instruments. The markets are characterized by the commodity that is traded on them (bioenergy or other agrarian products). There is a fixed demand for each of the commodities. It is a parameter of the market model. The market's state variables are the current market price for the product that is traded and the current total supply of it, which is generated by the agents.
We tested six policy instruments which differ in their designs. However, they have in common that they are economic incentives or disincentives. An overview is given in Table 2.3. The parameter of the policy instruments determines the strength of the incentive. Depending on the design of the policy instrument, it is either a "tax rate" or a "payment rate". The state variable of the instruments is the amount of the tax or the payment. It is specific for every cell and every production decision and determines the amount of the tax or the payment together with properties of the spatial entities.
The exogenous drivers of the model are the market demands. The other drivers are policy aims, which are implemented by policy instruments.
The model includes space implicitly, because each agent cultivates a spatial unit. One time step represents an agricultural production period, that consists of planning, sowing, growing, harvesting and selling the crop.

I.iii Process overview and scheduling

The scheduling of the model is illustrated in pseudocode in listing 2.1. A simulation run is divided in two blocks: the pre-simulation and the main simulation. The pre-simulation is run before the main simulation and differs from it in two aspects:

1. Restriction to the land use options "Other agrarian production" and "no cultivation"(no option to produce bioenergy)

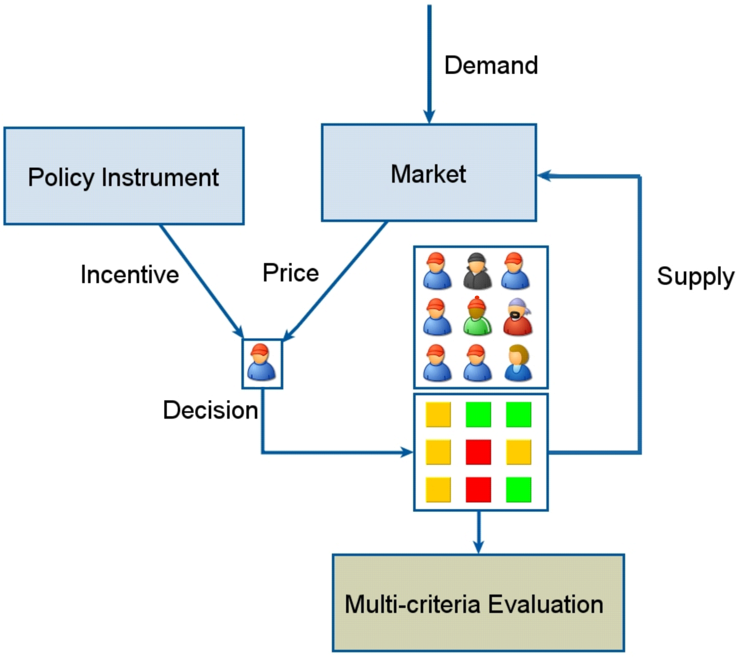

Figure 2.1.: Overview of the modeling framework

2. Absence of policy instruments

The function of the pre-simulation is to allow the system to reach an equilibrium with respect to market prices and percentages of land use for other agrarian production and no cultivation. This is necessary, because we want to disentangle the effect of different drivers, i.e. to study the additional effect of a specific bioenergy demand and one of the policy instruments. Therefore, we have to start the main simulation from an equilibrium between other agrarian production and fallow cells. The model region is a homogeneous agrarian region, hence we consider it plausible that agriculture is practiced as far as the economic conditions allow, before the appearance of a demand for bioenergy.
The duration of the pre-simulation is 20 time steps. The duration of the main simulation is variable.

A single time step comprises the calculation of the policy incentive for every agent (if applicable), a land use decision by every agent, calculations of the market prices after agent decisions and an update of the ecological submodel for each cell. The agents decide sequentially. We are aware that this design decision has consequences for the model behavior (Caron-Lormier et al., 2008). This point is further discussed in Chapter 3.
To make their decision the agents calculate the profit for every land use option. Then they choose the option which yields the maximum profit (decide()-function) and im-

plement it on their cell (cultivate-function()).

After these steps the C-stock of the cell is updated and the emissions are calculated. The C-stock of a cell is related to the land use on it. When a cell is under cultivation (of either bioenergy or other agrarian goods) we assume that the crop holds the minimum C-stock (i.e. value of the parameter minimum C-stock). The C-stock is removed and used annually and grows again to the same amount during the year. We model this in an aggregate form (i.e. the removal and regrowth of the C-stock are not explicitly modeled).
When the cell is not under cultivation, succession takes place on it. The C-stock grows, starting from the minimum C-stock. This is modeled by using a discretized logistic growth function. The new C-stock is calculated annually as well.
When a cell is taken under cultivation the vegetation on it is cleared and the cultivation takes place in the same time step. This causes a C-emission into the atmosphere.
As long as the cell is under cultivation, there are C-emissions from land use (e.g. from the production of fertilizer, the use of machinery, pesticides etc.). If the cell is used for the cultivation of bioenergy, the energy crops will substitute fossil fuels. This leads to an emission reduction which is subtracted from the emissions.
After the agents‘ decision and an update of the ecological submodel and the emission calculations, market prices are calculated (taking into account the supply generated by the agent that has just made its decision). Then the next agent decides.
At the end of one decision round, the evaluation criteria for the land use pattern that has emerged are calculated (e.g. the total harvest or the atmospheric or terrestrial C-stocks).

II Design concepts

II.i Theoretical and empirical background

As we mentioned in the Purpose section, it is our goal to create a reference version of the model that is close to established theory. We built large parts of the model on microeconomic theory, because despite criticism it is still a theory that is widely accepted and has a considerable explanatory power.
One of the central concepts that we used from economic theory are markets that are characterized by a supply and a demand (e.g. Mankiw and Taylor, 2006, Engelkamp and Sell, 2007). There are two reasons for our decision to model the market mechanism explicitly: 1) Market incentives are coupled to the land use system by (external) changes in demand. This allowed us to model the effect of changes in external drivers on the land use system. 2) The markets that we modeled are system endogenous. This means that the agents generate all the supply to meet a demand that is externally given. This also creates a feedback between the agents, because the supply that they generate influences the market prices. Modeling such a market mechanism allows to analyze the performance of policy instruments against potentially competing market incentives.

Listing 2.1: Pseudocode of the model‘s processes and scheduling

```
Initialize()

/* Pre−simulation without policy instruments
// and without bioenergy
*/

program Simulation
for t:=0 to 19 do
    for i:= 0 to N–1
        ChooseAgent()
        CalculateProfitsForTheDifferentLandUseOptions()
        Decide()
        Cultivate()
        CalculateC−StockOfCell()
        CalculateEmissionFromCell()
        CalculateMarketPrices()

// Main−simulation

for t:=0 to u do
    CalculateEvaluationCriteria()
    for i:= 0 to N–1
        ChooseAgent()
        CalculatePolicyIncentive()
        CalculateProfitsForTheDifferentLandUseOptions()
        Decide()
        Cultivate()
        CalculateC−StockOfCell()
        CalculateEmissionFromCell()
        CalculateMarketPrices()

end
```

Against the background of globalized agricultural markets, the assumption of fully endogenous markets may seem to be rather abstract. However, it has the advantage that we can model the consequences of the hypothesis that bioenergy couples energy markets with other agricultural markets (e.g. FAO, 2008, WBGU, 2009), which is highly relevant in the current debate.

With respect to the policy instruments we use concepts from environmental economics. We use the concept that a policy goal is to resolve externalities (in this case climate change by C-emissions from land use) by taxes or subsidies (Pigou, cited in Voigt, 2009). Therefore, the taxes that we test are oriented at Pigouvian taxes, which make the polluter pay for the emission that she causes. We also use instruments that subsidize the reduction of C-emissions through the conservation of ecosystem C-stocks. These instruments use the concept of payments for ecosystem services. The idea is to pay land users for the services that the ecosystem on their land generates (Engel et al., 2008). In this case these services are C-storage and sequestration.

Carbon accounting as proposed by IPCC (2007) is an important concept that is used for the evaluation of the land use patterns from a climate perspective. We use adapted versions of equations that are stated in Annex II of IPCC 2007 (change in C that is stored in biomass, emissions from land use). In addition, we use the concept of life cycle assessment which aims to describe the environmental impact of a product through its entire life cycle (e.g. Cherubini et al., 2009, Davis et al., 2009, Cherubini and Strømman, 2011). This is done in order to evaluate the climate impact of bioenergy which can be used to substitute fossil fuels during its further life cycle.

The agent‘s decision model is a myopic *Homo oeconomicus*. We chose this decision model to be compatible with established economic theory. The design concept behind this choice is to create a reference that can later be compared with more complex agent‘s decision models.

For the ecological submodel we use a logistic growth function. We chose this function, because it is suited to model the general pattern of biomass growth during succession (Odum, 1969, Zeide, 1993, Haberl, 2013).

II.ii Individual decision making

In the decision process land user agents decide on the land use in their cell in the next time step. They choose between three forms of land use: other agrarian production, bioenergy production and no cultivation. The decision is modeled on a highly aggregate level (i.e. decisions on the allocation of labor, or choices of buying and selling are not explicitly modeled).

The agents are fully rational *Homines oeconomici*. This is implemented by assuming that they have a constant preference for the land use option that will yield the maximum net profit. In addition, other assumptions from rational choice theory are

used: 1) The agents have the cognitive ability to compare the outcome of each possible action. 2) They have full information concerning the demands for the different goods and the total supplies (including the increased total supply that would result from their choice to produce). However, their full information is limited, because they do not know how the actions of other agents influence the prices.
In detail the decision is modeled as follows: the agent first calculates the profit for the available land use options. If there are policy instruments, the land-user accounts for the incentives that they set in its calculations. If, for example, there is a tax on the destruction of C-stocks implemented, the land user considers the tax-amount when it calculates the revenue of changing from no cultivation to another form of production. Then it picks the option that yields the maximum profit. “No cultivation” (i.e. fallow cell) is chosen when the expected profit from the alternative options is below 0.
By these choices the agent adapts its agricultural production to current economic and political conditions (the market‘s supply and demand, costs and incentives from policy instruments).
In the reference version of the model which is presented in this thesis, neither social norms, nor spatial and temporal aspects or uncertainty are included in the model.

II.iii Learning

Learning is not included in the model.

II.iv Individual sensing

In order to make its decision the agent needs to know its current production. In addition, it is aware of the costs that are related to the different production options in the next time step. When policy instruments are applied, the agent knows of the current amount of the tax or the payment that applies to the use of its cell.
To calculate the revenues of the different options the agent senses the current market demand and supply. Its full rationality implies that it knows the markets price-functions as well (remember that it calculates expected prices).
The agent does not perceive other agents state variables directly. However, it knows the total supply (which is generated by all agents) at the moment that it decides. The spatial scale of sensing is global with respect to the exogenous (state) variables and local with respect to the agents individual costs and the amount of individual policy incentives.
The sensing processes are not modeled explicitly. They are accurate and free of costs.

II.v Individual prediction

While the individual agent is not able to predict changes in market conditions and policies, it is able to predict the consequences of its production decision on the market price. To make this prediction it uses the information that was mentioned in II.iv (Individual sensing). The agent is assumed to use its ability to choose rationally to

make the prediction.
The agent is not erroneous in its prediction process. It realizes the profit from the land use option that it chooses (remember that the production decision, cultivation and selling of the crop are modeled in an aggregated way).

II.vi Interaction

The interactions between the agents are indirect, because they are mediated by the market mechanism. The demand and the total supply that the other agents generate influence the market price that a single agent can obtain from the production of a product. The demand is externally given. The lower it is, the more does a single production decision change the expected profits for the other agents (and vice versa). The demand therefore mediates the degree of interaction between the agents.

II.vii Collectives

There are no collectives in this model.

II.viii Heterogeneity

In this reference version of the model we use homogeneous agents (cf. section I.i and I.ii).

II.ix Stochasticity

The model is deterministic except for the decision sequence of the agents. We use the same random order of agent decisions for all simulation runs.

II.x Observation

Our goal is to evaluate the effect of the introduction of bioenergy on multiple criteria. This could include, for example, economical criteria like surplus, prices or the distribution of profits among the agents. Ecological criteria like the amount and age of fallow cells are also feasible. In this thesis we focus on the total harvest of the products, respectively the number of fallow cells and the carbon balance of the model region. We chose this criteria, because of their relevance in the bioenergy debate.

In the model version that is presented in this thesis, the harvests reach an unique equilibrium (cf. Chapter 3). For the measurement we chose a time step were the equilibrium was reached.
In contrast to the harvests, the climate-related state variables do not generally reach an equilibrium (cf. Chapter 3). Different relevant state variables can be considered:

1. The terrestrial C-stock ($C^{Ter}(t)$) is calculated by summing up the current C-stocks of all cells at time t.
2. The atmospheric C-stock (C^{Atm}) is a cumulative measure of the emissions and emission reductions from all cells over a time period. These are added up after every time step.

The advantage of using C^{Atm} as a measure of the climate impact of bioenergy is that it includes emissions from land use change which occur only once (when a fallow cell is converted for agricultural production) as well as emissions that accrue constantly. The decisions of the individual agents determine the land use patterns. Therefore, these are emerging properties of the model. The C-stocks of the cells are determined by the agents‘ decisions. Hence, C^{Atm} and C^{Ter} are emergent as well.

III Details

III.i Implementation Details

The model was implemented in C++ using a Gnu compiler on a Windows system. The source code is available upon request.

III.ii Initialization

The model is initialized with 100 agents and cells. All cells are not under cultivation. Their C-stock is maximal. We used the same initialization for all analyses. We chose this initialization, because our design of the analysis is to start from an equilibrium of cells that either produce other agrarian goods or are not under cultivation.

III.iii Input Data

The model does not use input data.

Table 2.1.: Overview of the models parameters.

Symbol	Connotation	Range	Unit
N	Number of agents	$\in \mathbb{Z}+$	–
u	Number of time steps in the main simulation	$\in \mathbb{Z}+$	Years
j	Product j	$\{Ag, Be, Fa\}$ [1]	–
D^j	Demand for j	$\in \mathbb{R}+$	Money units per decision step
c_i^j	Production costs of cell i for the production of j	$\in \mathbb{R}+$	Money units
TC	Costs for changing production	$\in \mathbb{R}+$	Money units
θ_{Max}	Maximum C-stock of a cell	$\in \mathbb{R}+$	Mass units
θ_{Min}	Minimum C-stock of a cell	$\in \mathbb{R}+$	Mass units
ψ	Maximum C-sequestration rate of a cell	$\in \mathbb{R}+$	Mass units
ε_L	C-emission reduction by bioenergy during its life cycle	$\in \mathbb{R}-$	Mass units
τ	Strength of the incentive	$\in \mathbb{R}+$	Money unit per mass units

[1] Ag = Other agrarian production, BE = Production of energy crops, Fa = No cultivation

Table 2.2.: Overview of the models state variables.

Symbol	Connotation	Range	Unit
$G_i^j(t)$	Profit that agent i generates by producing j	$\in \mathbb{R}$	Money units
$h_i^j(t)$	j-harvest in a cell	$\{0, 1\}$	Mass units
$p^j(t)$	Market price for j	$\in \mathbb{R}+$	Money units per mass unit
$e_i^j(t)$	C-emission of a cell through the production of j	$\in \mathbb{R}+$	Mass units
$\theta_i(t)$	C-stock of a cell	$\in [\theta_{Min}, \cdots, \theta_{Max}]$	Mass units
$T_i^j(t)$	Tax or subvention that agent i pays/obtains	$\in \mathbb{R}+$	Money units
$H^j(t)$	Total harvest of j in the region	$\in \mathbb{Z}+$	Mass units
$C^{Ter}(t)$	Terrestrial C-stock	$\in \mathbb{R}$	Mass units
$C^{Atm}(t)$	Atmospheric C-stock	$\in \mathbb{R}$	Mass units

Land use decision

$$G_i^j(t+1) \xrightarrow{j} Max! \tag{2.1}$$

The agent is a *Homo oeconomicus*. This is modeled by making it choose the production option $j \in \{oAg, BE, Fa\}$ that maximizes its profit in the next time step.

Profitfunction of an agent:

$$G_i^j(t+1) = \begin{cases} p^j(t+1) \cdot h_i^j(t+1) - c_i^j - TC - T_i^j(t+1), & j = \{Ag, BE\} \\ -T_i^j(t+1), & j = Fa \end{cases} \tag{2.2}$$

The agents calculate the profits for a land use option by subtracting costs from revenues. The revenues are generated by selling the harvest at the market price. The costs consist of production costs (c_i^j) and costs for changing production (TC). When a policy instrument is applied, the agent considers the incentive that it sets in its calculation ($T_i^j(t)$).
When the agent chooses “no cultivation”, there are no revenues from the vending of harvest. However, policy incentives apply.

The agents are fully rational. Therefore, they account for the change in the total supply by the harvest that they potentially produce $(H^j(t) + h_i^j)$. In detail, their calculation of revenue is:

$$p^j(t+1) \cdot h_i^j(t+1) = \frac{D^j}{H^j(t) + h_i^j} \cdot h_i^j(t+1) \tag{2.3}$$

Transformation costs:

$$TC = \begin{array}{cccc} \mathbf{j(t)\backslash j(t+1)} & \mathbf{Ag} & \mathbf{BE} & \mathbf{Fa} \\ \mathbf{Ag} & 0 & \mathrm{TC}_{Ag\to Be} & 0 \\ \mathbf{BE} & \mathrm{TC}_{Be\to Ag} & 0 & 0 \\ \mathbf{Fa} & \mathrm{TC}_{Fa\to Ag} & \mathrm{TC}_{Fa\to Be} & 0 \end{array} \tag{2.4}$$

In addition to production costs, the agent pays transformation costs when the form of land use is changed. These can be specific for the different possible land use changes.

Markets

Price function for p^j:

$$p^j(t) = \frac{D^j}{H^j(t)} \quad \text{with} \quad H^j(t) = \sum_{i=0}^{N-1} h_i^j(t) \tag{2.5}$$

The market price depends on the demand for a product D^j and its current supply H^j, which is a standard assumption in microeconomic theory (e.g. Mankiw and Taylor, 2006, Engelkamp and Sell, 2007).
The total supply is produced by all agents (i.e. the market is fully model endogenous). This allows to analyze the performance of policy instruments against potentially competing market incentives.
The demand is assumed to be fixed (i.e. price-insensitive). This is a reasonable assumption for the market for other agricultural products, because these can not be substituted in many cases. We are aware that this does not apply to bioenergy (which can be substituted by other energy carriers). However, we assume that the demand for bioenergy is politically fostered for strategic reasons, e.g. through blending quotas that generate a demand.

Table 2.3.: Overview of the policy instruments, payments for ecosystem services is abbreviated as PES

Instrument	**Functioning**	**Theoretical background**	**Incentive amount**
I 1: Tax C-stock	Agent has to pay for C-emissions when it destroys natural C-stock.	Pigou tax, polluter pays principle	Eq. 2.6
I 2: Payment C-stock	Agent obtains a payment for the natural C-stock on its cell in every time step.	PES	Eq. 2.7
I 3: Mix I 1 and I 2	Agent obtains a payment for the natural C-stock on its cell in every time step. When it destroys the C-stock it has to pay for the C-emissions.	See I 1, I 2, policy mix	Eq. 2.8
I 4: Payment C-seq	Agent obtains a payment for the C-sequestration by its cell in every time step.	PES	Eq. 2.9
I 5: Tax emission	Agent has to pay for all C-emissions from its land use (emissions from land use change, emissions from land use). The emission reduction by bioenergy is considered.	Pigou Tax, polluter pays principle	Eq. 2.10
I 6: Payment emission red	Agent obtains a payment for C-reduction from its land use (by emission reduction through bioenergy or C-sequestration by the vegetation).	PES	Eq. 2.11

Policy instruments

I 1: Tax C-stock (2.6)

$$T_i^j(t) = \begin{array}{cccc} \textbf{j(a)\textbackslash j(a+1)} & \textbf{Ag} & \textbf{BE} & \textbf{Fa} \\ \textbf{Ag} & 0 & 0 & 0 \\ \textbf{BE} & 0 & 0 & 0 \\ \textbf{Fa} & \tau \cdot \theta_i(a+1) & \tau \cdot \theta_i(a+1) & 0 \end{array}$$

For I 1 the agent has to pay the tax amount T_i^j when it changes its land use from fallow cell/no cultivation to the production of energy crops or other agrarian products. The amount depends on the tax rate τ and the size of the C-stock θ_i that is destroyed (which causes a C-emission). The size of the C-stock depends on the time a that the cells has not been under cultivation and is calculated for the next year (because the agent makes its decision for the coming production period).

I 2: Payment C-stock (2.7)

$$T_i^j(t) = \begin{array}{cccc} \textbf{j(t)\textbackslash j(t+1)} & \textbf{Ag} & \textbf{BE} & \textbf{Fa} \\ \textbf{Ag} & 0 & 0 & -\tau \cdot \theta_i(1) \\ \textbf{BE} & 0 & 0 & -\tau \cdot \theta_i(1) \\ \textbf{Fa} & 0 & 0 & -\tau \cdot \theta_i(a+1) \end{array}$$

I 2 grants a payment to the agent when it conserves the C-stock on its cell or creates a new C-stock instead of cultivation (i.e. it is rewarded for the ecosystem service of C-storage). The payment depends on the tax rate τ and the size of the existent C-stock θ_i in the following production period. If the agent creates a new C-stock, the payment is determined by the size of the C-stock that the cell can built up in one year. a denotes the age of the C-stock, τ is the incentive rate.

I 3: Mix (I 1 and I 2) (2.8)

$$T_i^j(t) = \begin{array}{cccc} \textbf{j(t)\textbackslash j(t+1)} & \textbf{Ag} & \textbf{BE} & \textbf{Fa} \\ \textbf{Ag} & 0 & 0 & -\tau \cdot \theta_i(1) \\ \textbf{BE} & 0 & 0 & -\tau \cdot \theta_i(1) \\ \textbf{Fa} & \tau \cdot \theta_i(a+1) & \tau \cdot \theta_i(a+1) & -\tau \cdot \theta_i(a+1) \end{array}$$

I 3 is a mix of the tax for the destruction of the C-stock (I 1) and the payment for the conservation of the C-stock (I 2). When the agent wants to convert its C-stock, it has to pay for the C-emission through this action. When it conserves its C-stock, respectively creates a new C-stock, it is rewarded for the C-storage. a denotes the age of the C-stock, τ is the incentive rate.

I 4: Payment C-sequestration (2.9)

$T_i^j(t) =$

j(t)\j(t+1)	Ag	BE	Fa
Ag	0	0	$-\tau \cdot (\theta_i(1) - \theta_{Min})$
BE	0	0	$-\tau \cdot (\theta_i(1) - \theta_{Min})$
Fa	0	0	$-\tau \cdot (\theta_i(a+2) - \theta_i(a+1))$

The incentive amount of I 4 is coupled to the ecosystem service of C-sequestration. When the land user switches from the production of energy crops or other agrarian production to no cultivation, it obtains a payment that is determined by the C-amount that its cell can sequester within the next production period (note that the growth of the C-stock begins from the value of θ_{Min}). When the agent conserves its C-stock, it is rewarded with an incentive that is proportional to the amount of C that its cell can sequester within one year. a denotes the age of the C-stock, τ is the incentive rate.

I 5: Tax emission (2.10)

$T_i^j(t) =$

j(t)\j(t+1)	Ag	BE	Fa
Ag	$\tau \cdot e^{Ag}$	$\tau \cdot (Max(0, e^{BE} + \varepsilon_L))$	0
BE	$\tau \cdot e^{Ag}$	$\tau \cdot (Max(0, e^{BE} + \varepsilon_L))$	0
Fa	$\tau \cdot (e^{Ag} + (\theta_i(a+1) - \theta_{Min}))$	$\tau \cdot (Max(0, e^{BE} + \varepsilon_L + (\theta_i(a+1) - \theta_{Min})))$	0

I 5 functions by taxing all C-emissions. This includes emissions from production (e^j), as well as emissions from land use change. For the production of bioenergy the emission reduction by bioenergy during its life cycle (ϵ_L) is considered in the calculation of the incentive (note that $\epsilon_L < 0$). If the agent changes from no cultivation/fallow cell to production, the net emission is accounted for (i.e. the difference between the C-stock that is destroyed and the C-stock of the crop θ_{Min}). If the fallow cell is converted for the production of energy crops, ϵ_L is accounted for. However, at high ϵ_L the tax does not become a payment. a denotes the age of the C-stock, τ is the incentive rate.

I 6: Payment emission reduction (2.11)

$T_i^j(t) =$

j(t)\j(t+1)	Ag	BE	Fa
Ag	0	$\tau \cdot (Min(0, e^{BE} + \varepsilon_L))$	$-\tau \cdot (\theta(1) - \theta_{Min})$
BE	0	$\tau \cdot (Min(0, e^{BE} + \varepsilon_L))$	$-\tau \cdot (\theta(1) - \theta_{Min})$
Fa	0	$\tau \cdot (Min(0, e^{BE} + \varepsilon_L + (\theta_i(a+1) - \theta_{Min})))$	$-\tau \cdot (Max(0, \theta(a+2) - \theta(a+1)))$

The goal of I 6 is to grant a payment for the reduction of emissions. This can be achieved through the cultivation of energy crops or through C-sequestration by a C-stock on the agent‘s cell. When the agent switches from other agrarian production to bioenergy or keeps producing energy crops, it obtains an incentive that is determined by the net emission reduction through bioenergy.

When the agent changes from no cultivation/fallow to bioenergy, the net emission through the conversion of its C-stock is taken into consideration.

The incentive for the emission reduction through C-sequestration equals I 4 (Payment

C-sequestration).
The minimum, respectively maximum conditions ensure that the payment does not become a tax. a denotes the age of the C-stock, τ is the incentive rate.

Ecological submodel

Change in C-stock (θ_i) of a cell that is not under cultivation (Fa) (2.12)

$$\begin{aligned}\theta_i(a+2) - \theta_i(a+1) &= \theta_i(a+1) + \psi \cdot \theta(a+1) \cdot (1 - \frac{\theta_i(a+1)}{\theta_{Max}}) - \theta(a+1) \\ &= \psi \cdot \theta(a+1) \cdot (1 - \frac{\theta_i(a+1)}{\theta_{Max}})\end{aligned}$$

The growth of the C-stock in cells that are not under cultivation is modeled with a discretized logistic growth function starting from θ_{Min}. This submodel was chosen because it allows to model the general pattern of biomass growth through succession (cf. section II.i Theoretical and empirical background).

C-balance of a cell (2.13) $E_i(t) =$

j(a)\j(a+1)	Ag	BE	Fa
Ag	e^{Ag}	$e^{BE} + \varepsilon_L$	$-(\theta_i(1) - \theta_{Min})$
BE	e^{Ag}	$e^{BE} + \varepsilon_L$	$-(\theta_i(1) - \theta_{Min})$
Fa	$e^{Ag} + (\theta_i(a+1) - \theta_{Min})$	$e^{BE} + \varepsilon_L + (\theta_i(a+1) - \theta_{Min})$	$-(\theta_i(a+2) - \theta_i(a+1))$

The C-balance of a cell depends on its use in the former and the current time-step. When the cell is not under cultivation (Fa), vegetation grows on it, leading to the built-up of a C-stock. The growth of the C-stock starts from θ_{Min}. Therefore, when a cell is changed to fallow land the net build-up after one time step is $\theta_i(1) - \theta_{Min}$ which is sequestered from the atmosphere.
When a cell is taken under cultivation the vegetation on it is cleared and the C-stock on it is emitted (note that cultivation takes place in the same time-step, leading to the built-up of a C-stock of the size θ_{Min}). As long as the cell is under cultivation there are C-emissions e^j from land use (e.g. use of machinery). If the cell is used for the cultivation of bioenergy, the energy crops will substitute fossil fuels. This leads to an emission reduction $-\epsilon_L$.

Evaluation criteria

Harvest (2.14)

$$H^j(t) = \sum_{i=0}^{N-1} h_i^j(t)$$

The total harvest is calculated by summing up the harvests that all individual agents generate.

Terrestrial C-Stock (2.15)

$$C^{Ter}(t) = \sum_{i=0}^{N-1} \theta_i(t)$$

The terrestrial C-stock is calculated by summing up the C-stocks of the single cells.

Atmospheric C-Stock (2.16)

$$C^{Atm}(t) = \sum_{t=0}^{u} E(u)$$

The atmospheric C-Stock is calculated by summing up the emissions and emission reductions from all cells over a time period u.

Testing of the submodels

If possible, the submodels were tested by comparison of analytically calculated results with simulation results. In addition, we verified that alternative model implementations (in NetLogo by the author and in Repast by J. Sebestyen) yielded the same results for a sample of parameter constellations (not shown here).

3. General system behavior

3.1. Introduction

Before we start with the analysis of bioenergy-related problems, we will give a first impression on the behavior of the model that we described in Chapter 2. We will present results for the models temporal dynamics and for functional responses of state variables that are relevant for the subsequent studies.
An emphasis of this chapter lies on understanding the models‘ market mechanism. The market in our model is model endogenous (in contrast to other approaches from agent-based modeling where market prices can be modeled in aggregation with other economic framework conditions as an external driver (e.g. Polhill et al., 2005, Schlüter and Pahl-Wostl, 2007) or as influenced by other factors than the supply that is generated by the agents (Balmann, 1997, Happe et al., 2006)). We choose fully model-endogenous markets (i.e. the agents generate the complete supply for the market and make decisions that are determined by market prices). The reason for this modeling decision is that it allows us to model the interplay between different drivers of land use change explicitly. However, it also creates the need to understand this central mechanism in detail.
In contrast to agent-based models, classical economic theory postulates a market equilibrium. Its existence can be explained by assuming a rational decision maker (e.g. Mankiw and Taylor, 2006, Engelkamp and Sell, 2007).
In contrast, agent-based models represent “generative social science”, hence they must not have equilibrium conditions imposed on them (Epstein, 2006, Tesfatsion, 2006). Results from agent interactions on a market do not necessarily converge to one equilibrium, even if the agents are rational profit maximizers (Tesfatsion, 2003, Arthur, 2006). In the model that is presented here, the market prices emerge from the interaction of autonomous agents as well. Therefore, we have to answer the question which dynamics occur when market prices emerge in this way.

3.2. Methods

In this chapter we use the modeling framework that was presented in Chapter 2 (without the policy instruments).
We make several homogeneity assumptions:

1. Homogeneity of the agents transformation costs TC (i.e. costs that accrue for a change of the land use on an agents‘ cell)

Table 3.1.: Parameter values of the model

Symbol	**Connotation**	**Value**	**Unit**
N	Number of agents	100	–
D^{Ag}	Demand for other agrarian products	40	Money units [1]
D^{BE}	Demand for bioenergy	[0,5,10,...,100]	Money units
k	Production costs	0.8	Money units
TC	Costs for changing production	0.1	Money units
θ_{Max}	Maximum C-stock of a cell	100	Mass units [2]
θ_{Min}	Minimum C-stock of a cell	10	Mass units
ψ	Maximum C-sequestration rate of a cell	0.3	Mass units
$e_i^j(t)$	C-emission of a cell through the production of j	1	Mass units
u	Time horizon	[50]	Years
ε_L	C-emission reduction by bioenergy during its life cycle	[0,-2,-4]	Mass units

[1] abbreviated as MU in the following,
[2] abbreviated as MaU in the following

2. Homogeneity between the costs for the production options (i.e. $c_i^{Ag} = c_i^{BE} = k$). This corresponds to the assumption of using average costs in a region.

The assumptions are made to facilitate comparisons between simulation results and results from classical economic theory. The model is run with one set of parameters (see Table 3.1), except for the demand for bioenergy D^{BE} and the C emission-reduction through bioenergy ϵ_L, for which a first partial sensitivity analysis is conducted.
In addition, we test the robustness of results to an alteration of the models default scheduling, which is a sequential update. In the experimental altered model scheduling we use a synchronous update. Pseudo code of the altered scheduling can be seen in listing 3.1.

Listing 3.1: Pseudocode of the model‘s scheduling assuming synchronous land use decisions

```
/* Pre−simulation without policy instruments
// and without bioenergy
*/
Initialize()
program Simulation
for t:=0 to 19 do
          CalculateMarketPrices()
     for i:= 0 to N−1
          ChooseAgent()
          CalculateProfitsForTheDifferentLandUseOptions()
          Decide()
          Cultivate()
          CalculateC−StockOfCell()
          CalculateEmissionFromCell()


// Main−simulation

for t:=0 to u do
     CalculateMarketPrices()
     CalculateEvaluationCriteria()
     for i:= 0 to N−1
          ChooseAgent()
          CalculateProfitsForTheDifferentLandUseOptions()
          Decide()
          Cultivate()
          CalculateC−StockOfCell()
          CalculateEmissionFromCell()
end
```

3.3. Results

3.3.1. Temporal dynamics

We start with an exploratory look at a single model run for one set of parameters. Figure 3.1 (a) shows the harvests and the market prices after every agent decision. It can be seen that the harvests increase and the number of cells that are not under cultivation declines until an equilibrium is reached. Figure 3.1 (b) shows the prices for other agrarian products and bioenergy. It can be seen that the price for bioenergy, that is considerably higher than the price for other agrarian products at $t_i = 0$, declines until it equals the price for other agrarian products.
Observing Figure 3.1 (a) and (b) in combination gives a first impression of the functioning of the market mechanism: time step t_i=0 represents the outcome of the pre-simulation in which the agents decide between other agrarian products and no cultivation (cf. Chapter 2). At the beginning, the price for bioenergy is considerably higher than the price for other agrarian products because the supply is low. Therefore, the first agents that are asked for their decisions change their production to bioenergy production. Each decision for bioenergy leads to a decrease of the bioenergy price and at the same time to an increase of the price for other agrarian products. Remember that the price function for $H^j > 0$ is $p^j(t) = \frac{D^j}{H^j(t)}$, so when an agent changes its land use from other agrarian production to bioenergy $p^{Ag}(t+1) = \frac{D^{Ag}}{(H^{Ag}(t) - h_i^{Ag})}$. This is larger then $p^{Ag}(t) = \frac{D^{Ag}}{H^{Ag}(t)}$. The agents behave this way until both prices are equal.
In the given exemplary model run some time steps follow where no land use changes are made. However, as soon as agents that own cells which are not under cultivation are asked, they enter the market. It can be seen that they enter either of the markets, which causes a decline of the prices. This happens until there is no incentive for any of the agents to change to another production option, as both prices are the same. After this point no more land use changes happen. The prices and harvests have reached an equilibrium.
At the end of the decision round, the land use patterns differ from the situation without a demand for bioenergy (at t_i=0): some agents that had formerly produced other agrarian products now produce bioenergy (which is reflected in a slightly higher price for Ag). Another important change is that there are no fallow cells left in the system at the end of the simulation. All of them have been converted either for bioenergy, or other agrarian production.
To test for path dependency of the equilibria, we ran simulations with randomly generated agent decision sequences. The results are shown in Figure 3.2 (a). It can be seen that a unique equilibrium is reached by different paths after one decision round. The same is true for the terrestrial C-stock (see Figure 3.2 (b)). The latter will be discussed in detail in the next section.

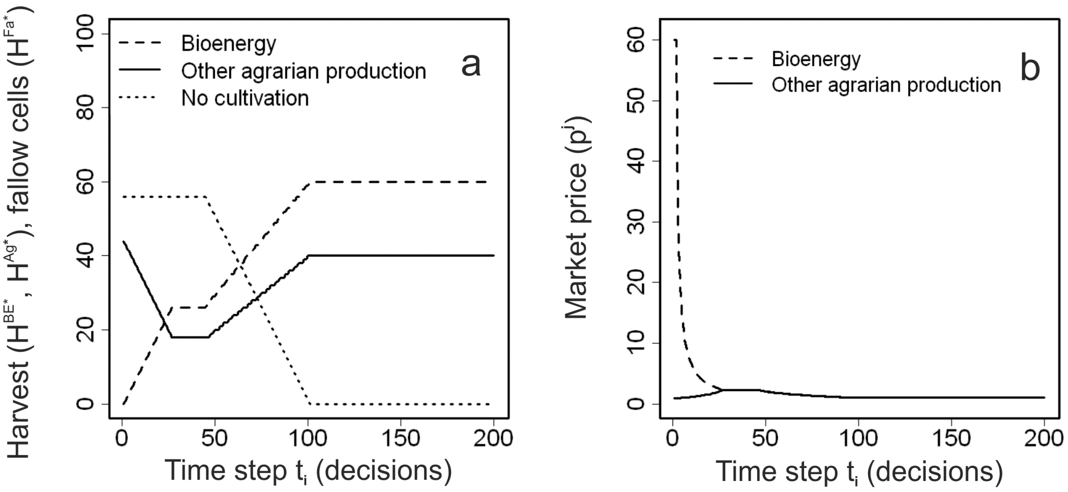

Figure 3.1.: Temporal dynamics of the harvests, respectively number of cells with no cultivation at the resulution of single decision steps. Parameter values: see Table 3.1.

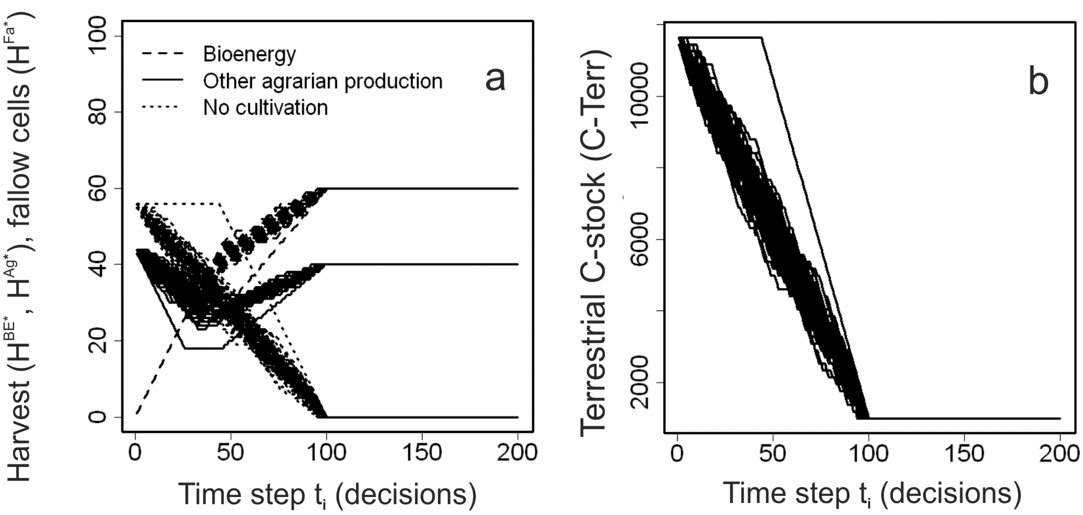

Figure 3.2.: Simulation results from 100 randomly drawn sequences of agent decisions. The equilibrium values are not influenced by the decision sequence. Parameter values: see Table 3.1.

3.3.2. C-balances

In the last section we showed that the introduction of a demand for bioenergy triggers land use changes. The next question that will be answered is how these changes are reflected in the C-balance of the system. The observed evaluation criteria are the terrestrial and the atmospheric C-stocks. Remember that the terrestrial C-stock is calculated by summing up the C-stocks of the individual cells. The atmospheric C-stock represents the accumulated emissions and emission reductions from all cells over a time-period u (see equations 2.2 and 2.2 in Chapter 2).

Figure 3.2 (b) in the last section shows the terrestrial C-stock (C^{Ter}) after each

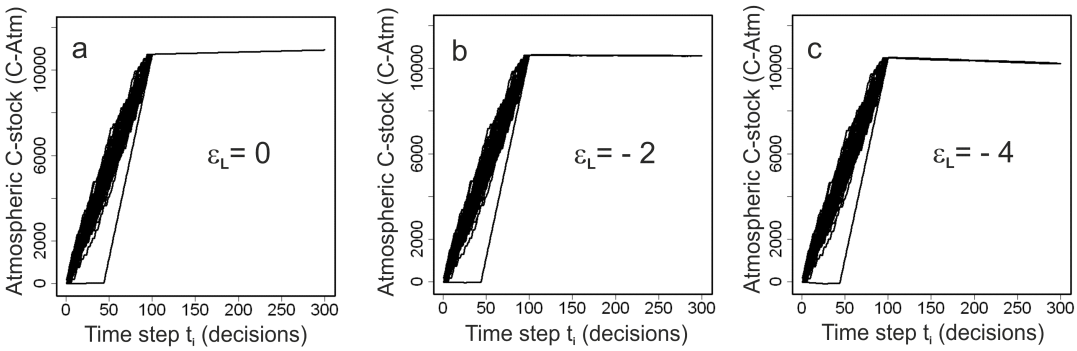

Figure 3.3.: Simulation results for the terrestrial and the atmospheric C-stock. Parameter values: see Table 3.1.

agent decision when a demand for bioenergy is introduced. It can be seen that C^{Ter} declines during the decision round until a constant minimum is reached. The decline correlates with the decline of the number of fallow cells. The reason is that cells under cultivation store less carbon than cells that have not been cultivated for some time.
The atmospheric and the terrestrial C-stocks are interlinked by three processes, namely emissions from land use change, emissions and emission reductions through bioenergy and C-sequestration by the vegetation. Figure 3.3 shows the atmospheric C-stock (C^{Atm}) after each agent decision. During the first decision round C^{Atm} increases markedly. The process that dominates here is "emissions from land use change", when fallow cells are taken under cultivation and their C-stock is released to the atmosphere. When there are no fallow cells left in the system, the other processes determine how C^{Atm} changes over time. This can be seen for different values for the emission reduction by bioenergy (ϵ_L) in the Figures 3.3 (a-c). When the emission reduction is zero (Figure 3.3 (a)), the emissions from land use accumulate leading to an increase in atmospheric C-stock. At high emission reductions (Figure 3.3 (c)) the opposite can be observed: the atmospheric C-stock decreases, because emissions from fossil fuels are continuously substituted.
It is important to notice that, contrary to the harvests in the region, C^{Atm} does not reach an equilibrium, as the emissions and emission reductions accumulate over the entire simulation period. To deal with this issue, a reference period has to be used.

3.3.3. The market equilibrium

At the beginning of this chapter we showed that the total harvests reach an equilibrium after one decision round. In this paragraph we take a closer look at the model rules to analytically calculate the equilibrium harvests.

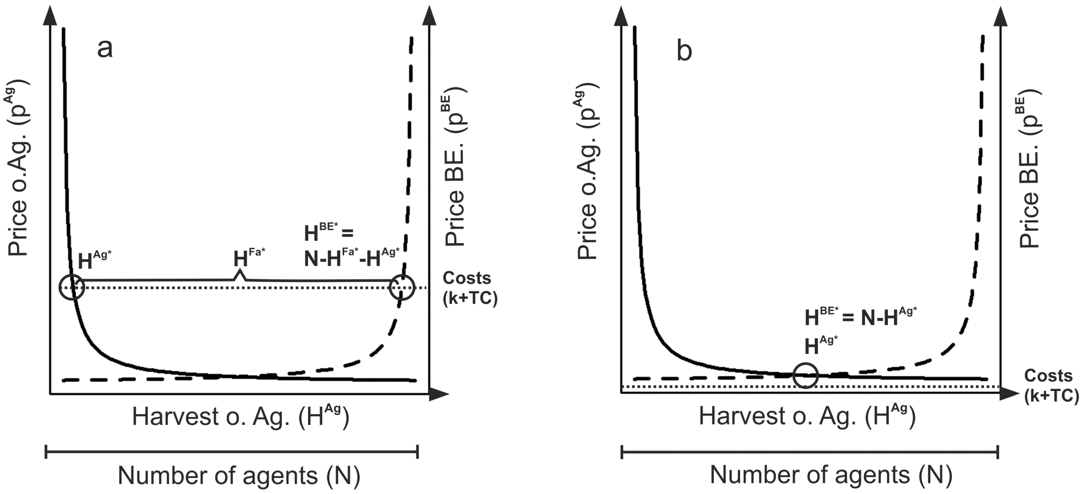

Figure 3.4.: Illustration of the market mechanism at constant demands. The solid and the dashed line show the prices for bioenergy and other agrarian goods as a function of the supply of other agrarian goods H^{Ag}. The left panel shows a setting with high production costs, the right panel a setting with lower costs k.

Figure 3.4 shows an illustration of the market prices as a function of the supplies $(p^j(H^j))$. The two markets are interlinked by the limited available land that can be used for production. Therefore, an increase of one unit of other agrarian products means a decrease of one unit of bioenergy or of fallow cells.
The agents are *Homo oeconomicus*, so following general equilibrium theory the equilibrium is situated where there is no incentive for any of them to change its land use. In this point all land use options yield the same profit. The model rule for the agents profit is: $G^j = p^j \cdot h^j - k - TC$ (equation 2.2 in Chapter 2). Hence, the market price and the costs influence the position of this point. The position of the equilibrium is either determined by the agents‘ production and transformation costs (Case 1, Figure 3.4 (a)) or by the intersection of the two price functions (Case 2, Figure 3.4 (b)). When the agents‘ production costs are high (Case 1), only a part of the agents can produce cost covering. Hence, there are fallow cells in the system because agents choose this option when cultivation would involve losses (i.e. $G^j < 0$). This can be used to formulate the condition for agents to change to or remain in production because they do so when $G^i > 0$.

Taking bioenergy as an example, the condition to choose this land use option is: $G^{BE} > 0$

$$\begin{aligned} \text{This is met when:} \quad & \\ p^{BE} &> k + TC \\ \Leftrightarrow \quad \frac{D^{BE}}{H^{BE}} &> k + TC \\ \text{which can be rearranged to:} \ \Leftrightarrow \ H^{BE*} &= \frac{D^{BE}}{(k+TC)} \end{aligned} \tag{3.1}$$

The same applies for other agrarian products:

$$H^{Ag*} = \frac{D^{Ag}}{(k+TC)} \tag{3.2}$$

$$\begin{aligned} \text{and as:} \quad N &= H^{BE*} + H^{Ag*} + H^{Fa*} \\ H^{Fa*} &= N - \frac{D^{BE} + D^{Ag}}{(k+TC)} \end{aligned} \tag{3.3}$$

In Case 2, when the agents' production costs are lower than the minimum possible prices, all agents use their cells for production and no fallow cells are left in the system. The latter fact can be used to learn about the conditions that distinguish Case 1 from Case 2:

$$\begin{aligned} \text{Cost covering production (Case 1) as long as:} \quad & \\ H^{Fa*} &> 0 \\ \Leftrightarrow N - \frac{D^{BE} + D^{Ag}}{(k+TC)} &> 0 \\ \Leftrightarrow D^{Ag} + D^{BE} &< N \cdot (k+TC) \end{aligned} \tag{3.4}$$

So at demands higher than $N \cdot (k+TC)$ all agents are in the production and decide between the cultivation of bioenergy and other agrarian products. In this case the condition to produce bioenergy is:

$$\text{Considering bioenergy:} \quad p^{BE} > p^{Ag}$$

$$\Rightarrow \quad H^{BE*} = N \cdot \frac{D^{BE}}{(D^{Ag} + D^{BE})} \tag{3.5}$$

$$\Rightarrow \quad H^{Ag*} = N \cdot \frac{D^{Ag}}{(D^{Ag} + D^{BE})} \tag{3.6}$$

The detailed calculations can be found in the appendix (section 3.5). The analytical solution of the market model reveals some of the model behavior. One insight is that there is a threshold value that distinguishes between a system with fallow cells and a

system without fallow cells. This threshold value is determined by the demands for the goods and the agents production costs. This is of interest, because cells that are not under cultivation play a crucial role for the C-balance of the region.
It can also be seen that the equilibrium harvests show two different functional responses to increases in demand. At $D^{Ag} + D^{BE} < N \cdot (k + TC)$ (when there are still fallow cells in the system) the harvests increase linearly with a slope of $\frac{1}{(k+TC)}$. The number of fallow cells decreases linearly with increasing demands (see Equation 3.3). When there are no fallow cells left in the system, the harvests do not increase linearly with the demand, but in a bell shaped curve. When the demand for one product increases, its harvests approach N whereas the harvests of the other products approach 0 (see Equations 3.5 and 3.6).

Comparison of analytically calculated results with simulation results

In the last section we named model behavior that has to be expected when the demand for one of the commodities increases. The next step is to compare these expectations with results from the agent-based model. Figure 3.5 shows the harvests for the products at an increasing demand for bioenergy. A comparison of the results that were analytically calculated with the simulation results reveals that the analytical model is a good approximation for the simulation results (the slight deviation of the simulated results is an effect of discretization).
The shapes of the curves match quantitatively and qualitatively. The model behavior that was inferred from the analytical considerations can be observed. The change in harvests is linear until $D^{BE} = N \cdot (k + TC) - D^{Ag}$ which is 50 for the chosen set of parameters. After that the curves are bell shaped.

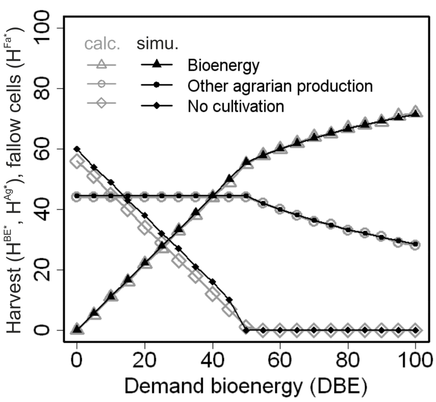

Figure 3.5.: Effect of an increasing demand for bioenergy on the land use for the cultivation of energy crops, of other agrarian products and no cultivation. Parameter values see Table 3.1.

3.3.4. No market equilibrium

In the previous sections we have shown that in the agent-based model harvests and prices quickly reach an equilibrium. In the last section of this chapter we test whether these findings are robust to the model‘s scheduling. A comparison at the default scheduling and the altered scheduling is shown in Figure 3.6 (a) and (b). When the agents decide simultaneously, the harvests oscillate instead of reaching an equilibrium.

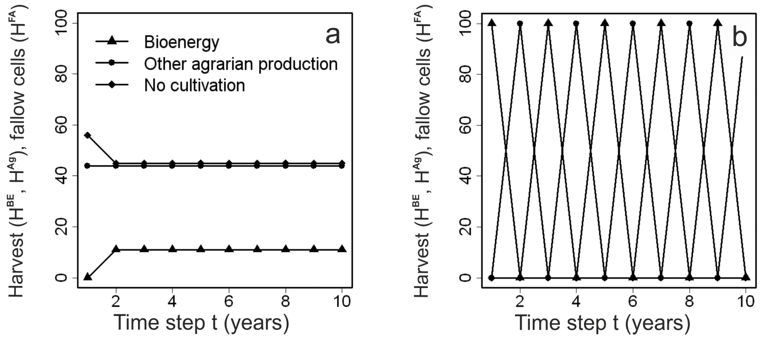

Figure 3.6.: Simulation results for two different schedulings. In the left panel, the agents decide sequentially and the prices are calculated between the decision steps. In the right panel, all agents decide and the prices are then computed. Parameter values: see Table 3.1, except $D^{BE} = 10$.

The reason for the oscillations is that, when all agents are asked for a decision and the profit for one product is slightly higher, all agents choose to produce this product. This leads to an oversupply of the product in the next time step, which causes very low prices. Consequently, all agents choose to produce the alternative product when they are asked in the next time step. In contrast to the harvests, the fallow cells reach an equilibrium at 0. The reason is that all fallow cells are converted instantly when the prices are high.

One insight from this result is that the expectations that where derived from the model rules in this Chapter do not apply anymore to the simulation model when the scheduling is changed. Another insight is that the model has two fundamentally different dynamics.

3.4. Discussion

In this chapter we gave a first overview over the model behavior. We showed that the model-endogenous market reaches an equilibrium that is not path dependent. The equilibrium is even analytically tractable when homogeneity assumptions are made. These results are useful for the design of the analysis of the subsequent studies.

Another finding with relevance for the next studies is that the atmospheric C-stock does not reach an equilibrium. The reason is that processes with different temporal dynamics contribute to it. Therefore a time horizon has to be chosen after which an evaluation takes place. This is an established approach in research that deals with the evaluation of options of climate-change mitigation (IPCC, 2007, Arnell et al., 2013, Scrieciu et al., 2013).

3.4.1. The results in the context of the bioenergy issue

One result from this chapter is that the land user agents change their land use towards bioenergy production in response to D^{BE}. This is a realistic process (FAO, 2009). However, the extent of the land use change that is triggered by a demand for bioenergy is very hard to measure (Searchinger et al., 2008, Lapola et al., 2010, Sterner and Fritsche, 2011). One reason is that bioenergy may trigger "market-mediated land use changes" (Witcover et al., 2013). These take place when the cultivation of bioenergy replaces the cultivation of other agrarian products. This leads to a decrease in supply. If the demand for the agrarian products remains constant, it may become economically attractive to convert areas that would not be under cultivation in the absence of a demand for bioenergy. Our model includes this relevant feedback, because all land use changes are linked by markets. Therefore the results include this effect. Hence, it can be used as a tool to model the response of the land use system to an increasing bioenergy demand under the realistic circumstances of different coexisting market demands as driving forces.
Another result concerning the land use change that is triggered by an increasing bioenergy demand was that cells which are not under cultivation are converted. Although these cells are not of economic value for the *Homo oeconomicus*-land user, they may have other important functions like the provision of various ecosystem services. This outlines a conflict that will be further analyzed in the next chapters. This chapter ends with a methodological reflection on the modeling of markets in agent-based models.

3.4.2. Challenges and benefits of using a classical economic general equilibrium approach as a theoretical background for an agent-based model

We demonstrated that it is possible to use a general equilibrium approach from economic theory as a theoretical foundation for an agent-based model. It is, however, a challenge to implement the strong assumptions that are made in this theory (e.g. time-continuity and agent homogeneity). All departures from the assumptions have to be carefully tested, because in dynamic models phenomena like path dependency and oscillations can occur. Creating a "reference" agent-based model that is compatible with classical economic theory allows to undertake this systematically. This strategy can be used to compare both theories (i.e. "generative social science" Epstein (2006) vs. microeconomic theory).
In a bachelor thesis in close cooperation with this project, Sebestyen (2012) relaxed the assumption of homogeneity between the agents. This was implemented by variation of their production costs and the areas they own. Sebestyen (2012) found that there are framework conditions where this leads to path dependency, or equilibrium

indeterminacy, a problem also described by Arthur (2006). However, there are also framework conditions where there is no difference between the homogeneous and the heterogeneous model versions. Another interesting result was the effect of the change of the agents decision sequence. It leads to fundamentally different model dynamics. Instead of equilibria oscillations occur. The same effect was found by Parker (1999) in a similar stylized agent-based model, where profit-maximizing agents decide between two land use options. The occurrence of this phenomenon is still compatible with economic theory where it is known as pork cycle to explain the pattern of cyclical changes in prices and supplies (Hanau, 1928). It applies to situations where there is a time lag between the investment decision and the selling of the products.
Despite the challenges described above we consider the use of an existent theoretical background important for coming up against the criticism that agent-based models tend to be ad-hoc (Feola and Binder, 2010). A benefit of building on general equilibrium theory is that the market model is analytically tractable. This is useful in several aspects. First, it allows to verify the model implementation by comparison of simulated and analytically calculated results. Secondly, analytical considerations are a tool of model understanding as they allow to predict functional responses to changes in parameters of interest. This was shown for the demand for bioenergy in this chapter. To conclude, established theories can be a useful foundation for agent-based models. These can then be used as a tool to identify under which conditions the theories are useful, by "growing" phenomena they describe, or by failing to do so (Epstein, 2006).

3.5. Appendix

In Case 1 an agent will choose production as long as it is profitable so $G^{BE} > 0$

$$G^j = p^j \cdot h^j - k - TC \qquad \text{(see equation 2.2)}$$

Considering the production of bioenergy:

$$\begin{aligned} p^{BE} &> k + TC \\ \Leftrightarrow \frac{D^{BE}}{H^{BE}} &> k + TC \\ \Leftrightarrow H^{BE} &< \frac{D^{BE}}{(k+TC)} \\ \Rightarrow H^{BE*} &= \frac{D^{BE}}{(k+TC)} \end{aligned}$$

Considering the other agrarian production:

$$\begin{aligned} p^{Ag} &> k + TC \\ \Leftrightarrow \frac{D^{Ag}}{(N - H^{BE*})} &> k + TC \\ \Rightarrow H^{BE*} &= N - \frac{D^{Ag}}{(k+TC)} \\ \Rightarrow H^{Ag*} &= \frac{D^{Ag}}{(k+TC)} \end{aligned}$$

From this, the number of cells with no cultivation can be derived:

$$\begin{aligned} H^{Fa*} &= N - H^{BE*} - H^{Ag*} \\ \Leftrightarrow H^{Fa*} &= N - \frac{D^{BE}}{(k+TC)} - \frac{D^{Ag}}{(k+TC)} \\ &= N - \frac{D^{BE} + D^{Ag}}{(k+TC)} \end{aligned}$$

As a contrast, in Case 2 the agents optimize between the two production options. In this case, no fallow cells are left in the system. This fact can be used to learn about the conditions that distinguish Case 1 from Case 2:

Cost covering production (Case 1) as long as:

$$\begin{aligned} H^{Fa*} &> 0 \\ \Leftrightarrow N - \frac{D^{BE} + D^{Ag}}{(k+TC)} &> 0 \\ \Leftrightarrow D^{Ag} + D^{BE} &< N \cdot (k+TC) \end{aligned}$$

At demands higher than $N \cdot (k+TC)$ the agents optimize between the two production options. In this case the harvests in the equilibrium are:

$$\begin{aligned}
\text{Considering bioenergy:} \quad & p^{BE} > p^{Ag} \\
& \frac{D^{BE}}{H^{BE}} > \frac{D^{Ag}}{H^{Ag}} = \frac{D^{Ag}}{(N - H^{BE})} \\
\Leftrightarrow \quad & D^{BE} \cdot (N - H^{BE}) > D^{Ag} \cdot H^{BE} \\
\Leftrightarrow \quad & D^{BE} \cdot N > H^{BE}(D^{Ag} - D^{BE}) \\
\Leftrightarrow \quad & H^{BE} < N \cdot \frac{D^{BE}}{(D^{Ag} + D^{BE})} \\
\Rightarrow \quad & H^{BE*} = N \cdot \frac{D^{BE}}{(D^{Ag} + D^{BE})}
\end{aligned}$$

Part II.

Using the agent-based model to analyze land use change in the context of bioenergy production

4. Study I: Understanding the impact of bioenergy in the land use system

4.1. Introduction

We have seen that bioenergy is politically fostered for multiple strategic reasons. Examples for policies to foster bioenergy include the European Union Renewable Energy Directive (RED) or the Renewable Fuel Standard (US-RFS2) in the United States. These policies function by creating a demand for bioenergy. However, after installing them it became obvious that the creation of a demand drives land use change. Land use change may include different processes: One possibility is the change of the production regimes, which can cause a change in C-emission rates. Another process can be the change from one form of production to another (e.g. other agrarian production can be replaced by the production of energy crops which have the potential to substitute fossil fuels). Further, a conversion of cells that had not been under cultivation can take place and may involve the destruction of terrestrial C-stocks.
All these processes affect the C-emissions and therefore the climate balance of land use. This may offset the expected climate change mitigation effect from bioenergy production, which is one of the goals of politically fostering bioenergy (Fargione et al., 2008, Searchinger et al., 2008, WBGU, 2009, Lange, 2011, Sterner and Fritsche, 2011, Haberl, 2013).

Our approach to understand the effect of bioenergy on the climate is an analysis of

1. The functional response of the climate balance (measured in terms of the changing C-stock in the atmosphere ΔC^{Atm}) to an increasing bioenergy demand D^{BE}

2. The factors and mechanisms that control the response

Our aim is to elaborate a classification of conditions under which an extension of bioenergy actually reduces ΔC^{Atm} (intended) or increases ΔC^{Atm} (unintended side-effect). Our model allows to analyze the effect of these framework conditions. Therefore we will use it in this chapter to analyze how the factors mentioned above affect the success of bioenergy to reduce ΔC^{Atm} and therefore to mitigate further climate change. We use the insights to formulate rules of thumb to characterize situations where politically fostering bioenergy will probably lead to unwanted side effects on the climate.

4.2. Methods

4.2.1. Design of the analysis

The aim of the analysis that is presented in this chapter is to assess the climate effect of an increasing bioenergy-demand under various economic, ecological and technological framework conditions. This is conducted to learn under which framework conditions the introduction of bioenergy may have unwanted side-effects.
The model has groups of parameters that describe the specific framework conditions: k, D^j and TC describe the economic framework conditions, θ_{Max}, θ_{Min} and ψ describe the ecological framework conditions and e^j and ϵ_L are the technological parameters. The latter two groups obviously influence the atmospheric C-stock. In addition, we showed in Chapter 3 that the economic parameters influence the atmospheric C-stock through effects of land use change. We also found that the considered time horizon u is influential. Therefore these parameters (with the exception of e^j and TC) will be in the focus of this study.
Our approach is a nested partial sensitivity analysis. The “core-simulation” of the analysis is a variation of the parameter D^{BE} to model an increasing bioenergy-demand. In order to assess the climate effect of this change, the difference in atmospheric C-stock C^{Atm} relative to a baseline without bioenergy is measured after a time horizon u:

$$\begin{aligned} &\Delta CAtm(t = u, D^{BE} = j) = \\ &CAtm(t = u, D^{BE} = j) - CAtm(t = u, D^{BE} = 0) \end{aligned} \tag{4.1}$$

The strategy of our analysis consisted of three steps:

1. Conduct the “core simulation” with 16200 different parameter constellations in order to assess general response types of ΔC^{Atm}.

2. Conduct a nested sensitivity analysis of the response types identified in step 1 with respect to the relevant parameters.

3. Exposure of important central mechanisms.

The parameter ranges that we explored can be found in table 4.1.

Table 4.1.: Parameter values of the model

Symbol	Connotation	Value	Unit
N	Number of agents	100	–
D^{Ag}	Demand for other agrarian products	[0,6,12,..,174]	Money units [1]
D^{BE}	Demand for bioenergy	[0,5,10,...,100]	Money units
k	Production costs	[0,0.006,...,1.74]	Money units
TC	Costs for changing production	0.1	Money units
θ_{Max}	Maximum C-stock of a cell	[50,100,200]	Mass units [2]
θ_{Min}	Minimum C-stock of a cell	10	Mass units
ψ	Maximum C-sequestration rate of a cell	[0.1,0.2,0.3]	Mass units
$e_i^j(t)$	C-emission of a cell through the production of j	1	Mass units
u	Time horizon	[25,50,100,500]	Years
ε_L	C-emission reduction by bioenergy during its lifecycle	[0,-1.1,-1.5,-4,-10]	Mass units

[1] abbreviated as MU in the following,
[2] abbreviated as MaU in the following

4.3. Results

4.3.1. The impacts of an increasing bioenergy demand

The first step of the analysis consists of a description of the change in atmospheric C-stock ΔC^{Atm} relative to a baseline that represents a situation without bioenergy (C^{Atm} at $D^{BE} = 0$). The functional response ΔC^{Atm} vs. (D^{BE}) will be referred to as "Response Pattern" in the subsequent analysis, because it is used to analyze the response of the environmental state variable to increasing pressure by the driver D^{BE}. We found that, depending on the parameter constellation, three different response patterns occur.

Figure 4.1 shows some exemplary results for three different framework conditions. In order to foster the identification of the underlying mechanisms, we additionally display the respective responses of the land use patterns.
We found that, depending on the parameter constellation, three different response patterns can be distinguished.

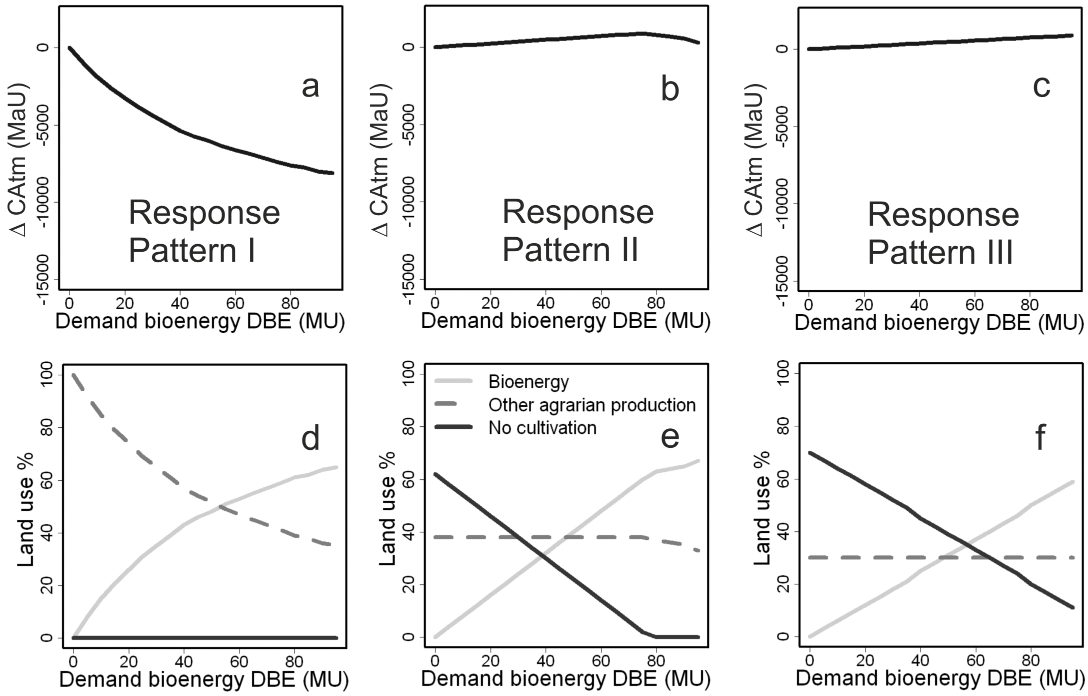

Figure 4.1.: Characteristic simulation results from the core sensitivity analysis. Three response patterns of atmospheric C-stock can be distinguished.

The ΔC^{Atm} can decrease steadily with an increasing bioenergy demand (Figure 4.1 a). The opposed case can also be observed: increasing the demand for bioenergy leads to a continuous increase of ΔC^{Atm} (Figure 4.1 c). A third possibility is an intermediate situation in which increasing the demand for bioenergy leads to an increase of the atmospheric C-stock at the beginning of the curve. Then there is an inflection point and for further increases of D^{BE} ΔC^{Atm} decreases steadily. In short: bioenergy can succeed or fail as a measure of climate change mitigation. Missing the goal (Pattern II and III) means that there is a need for further policy action to mitigate unwanted side effects of the fostering of bioenergy.

The increasing bioenergy demand leads to a change of land use patterns. This change is reflected in the atmospheric C-stock. Figure 4.1 (d-f) shows the land use change for the parameter constellations that lead to the Response Patterns I - III. Lets consider Pattern I, where the introduction of bioenergy leads to a decrease of ΔC^{Atm}. Looking at the percentage of land use forms it can be seen that all cells are in use, even at $D^{BE} = 0$. So when a cell is converted to bioenergy production, it always substitutes other agrarian production. This is beneficial for the climate, because bioenergy is used to substitute fossil fuels.
The land use change that leads to Pattern II is different: at $D^{BE} = 0$ two forms of land use are in the system ("production of other agrarian goods" and "no cultivation").

When D^{BE} increases, land users switch from " no cultivation" to the production of bioenergy. This includes the destruction of ecosystem C-stocks, which leads to emissions from land use change. These cause an increase of ΔC^{Atm}. Note that there is a peak of ΔC^{Atm} at the D^{BE} that leads to a destruction of all fallow cells during a simulation. If D^{BE} increases beyond this value, ΔC^{Atm} decreases, because, in addition to the destruction of all fallow cells, some cells that were used for other agrarian production are converted to the production of bioenergy.

Pattern II reveals a fundamental trade-off concerning climate-protection by bioenergy: the goal of climate change mitigation may be missed, because ecosystems, which also provide climate change mitigation by C-storage and sequestration, may be destroyed through land use change leading to emissions from the C-stock. Vice versa, land that is dedicated to the conservation of ecosystems can not be used for climate change mitigation by bioenergy.

When Pattern III is observed, all land use forms exist. However, in contrast to Pattern II, the percentage of other agrarian production does not change. Only fallow cells are converted, which leads to an increase of the atmospheric C-stock.

According to the strategy of our analysis, the next step is a sensitivity analysis of the response types (these are the Response Patterns). We begin with the economic parameters.

4.3.2. The influence of the economic framework conditions on the Response Pattern formation

In this step of the nested sensitivity analyses we investigate the occurrence of the response patterns at parameter combinations of agents production costs k and the demand for other agrarian goods D^{Ag}, while the other tested parameters are kept constant. This allows to map the economic framework conditions where the introduction of bioenergy bears a high risk of unwanted climate effects (Pattern III) or where the risk is intermediate (Pattern II) or low (Pattern I). We will refer to this results as "Pattern Maps" in the further analysis. An example for such a "Pattern Map" is shown in figure 4.2.

This figure reveals that there is a clear relationship between the emergence of a certain Response Pattern (I, II or III) and the tested economic parameters. It can be seen that the patterns occur in clearly delineated zones. In addition, there is a trend: a decrease of k and an increase of D^{Ag} lead to a shift of the observed patterns from Pattern III to Pattern II and then Pattern I.

Pattern I dominates under conditions that are characterized by low production costs and/or high D^{Ag}. This is consistent with the observations of the underlying land use patterns from the last paragraph, because at low production costs and/or high D^{Ag} cultivation is profitable for all agents. This means that all cells are under cultivation and there are no fallow cells to be destroyed for the cultivation of bioenergy.

On the opposite side of the tested parameter space (high k, low D^{Ag}), the increasing D^{BE} causes Response Pattern III. This is in line with the results from the previous section as well, because at low demands for other agrarian goods and/or high produc-

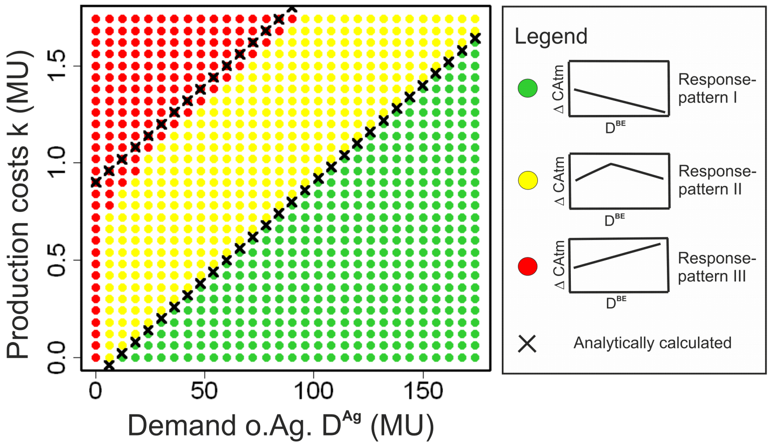

Figure 4.2.: Response Patterns at different economic framework conditions. The simulation results for ΔC^{Atm} vs. D^{BE} were classified with respect to membership to one of the Response Patterns. Black crosses mark results from an analytical calculation of the limits of the Patterns' occurrence. Parameter values: see Table 4.1.

tion costs production is not profitable for many agents. Subsequently there are many fallow cells in the system which are converted to bioenergy at increasing D^{BE} leading to emissions from the destruction of terrestrial C-stocks. The trade-off Pattern II occurs in between these regions in the parameter space.
Figure 4.2 also reveals that the lines that describe the borders between the different zones are linear. This is an interesting observation, but not fully understood so far.

Analytical approximation of the Pattern Map

In Chapter 3 we have derived approximation formulas for the percentages of the different land use forms in the region (H^{BE*},H^{Ag*},H^{Fa*}). These are formulated using the economic parameters. Can they also be used as a tool to estimate the parameter space that leads to a specific response pattern? We found that Pattern I occurs under an economic situation where all cells are in use for cultivation at the moment when bioenergy is introduced. This means at the reference value $D^{BE} = 0$ we have $H^{Fa} = 0$. Equation 3.5 describes the threshold for the existence of uncultivated cells in the system using the economic parameters:

$$\begin{aligned}
&\text{Cost covering production (Case 1) as long as:} \\
&H^{Fa*} > 0 \\
\Leftrightarrow\ &N - \frac{D^{BE} + D^{Ag}}{(k + TC)} > 0 \\
\Leftrightarrow\ &D^{Ag} + D^{BE} < N \cdot (k + TC)
\end{aligned}$$

It can be rearranged to calculate the threshold for production costs (k^{crit}), below which there are no fallow cells left in the system at $D^{BE} = 0$:

$$k^{crit} = \frac{D^{Ag}}{N} - TC \tag{4.2}$$

Concerning the distinction between Pattern II and Pattern III we know from the observations of the land use patterns that Pattern III occurs when there are fallow cells in the system at the maximum tested value for bioenergy (here $D^{BEmax} = 100$). Again, equation 3.5 can be reformulated to calculate the threshold expressed by agents production costs k:

$$k^{crit} = \frac{D^{Ag}}{N} + \frac{D^{BEmax}}{N} - TC \tag{4.3}$$

The comparison between analytically calculated results and simulation results in Figure 4.2 shows that the equations yield good approximations for the results from the agent-based model. The equations explain the observation that the limits of the response patterns are a linear function of D^{Ag}.

As an additional information the analytical considerations reveal that the transformation costs TC determine the extent of the response patterns as well. At higher TC the extent of Pattern I would be smaller. This means the parameter space where bioenergy meets the goal of climate change mitigation would be narrower. The extent of Pattern III would be larger. That means the area where bioenergy is likely to miss the goal of climate change mitigation would be larger.

The results that were presented so far suggest that the system response to an introduction of bioenergy can be entirely explained by the existence of fallow cells, respectively by changes of the number of cells that are not under cultivation. However, this is not the whole picture as there are also the emissions from production and the emission reductions by bioenergy that contribute to ΔC^{Atm} after a period of u years. Some of the emissions are nonrecurring (emissions from the destruction of ecological C-stocks) and some of them accrue constantly in time (emissions from production and emission reductions by bioenergy). This can be formalized:

$$C^{Atm}(u) = \sum_{i=0}^{N} \theta_i(u) - \theta_i(0) + H^{Ag*} \cdot u \cdot e^{Ag} + H^{BE*} \cdot u \cdot (e^{BE} + \epsilon_L) \qquad (4.4)$$

As a next step it is interesting to see the extent to which the Pattern Maps depend on all other framework conditions: the technological (especially ϵ_L), the ecological (especially θ_{Max}) and the time horizon u.

4.3.3. The influence of the technological conditions and the time horizon on the Pattern Maps

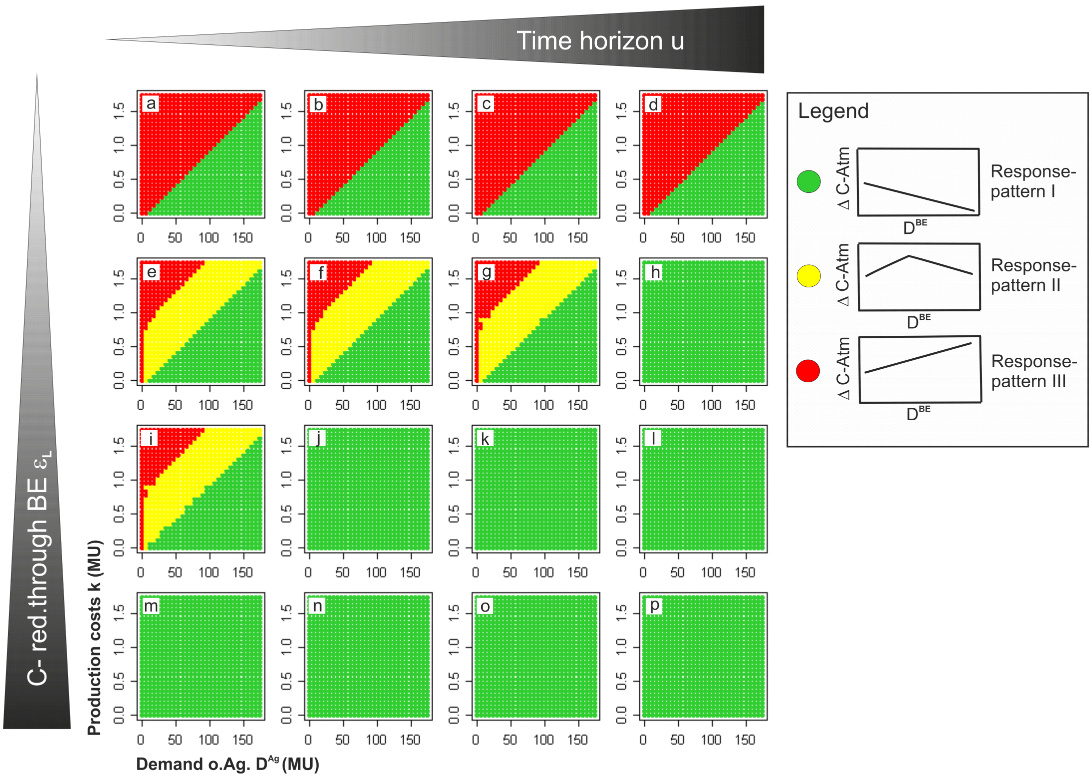

Figure 4.3.: Influence of C-emission reduction potentials of bioenergy and reference periods on the Pattern Maps. Parameter values: see Table 4.1.

Figure 4.3 shows the Pattern Maps (the Response Patterns in dependence on the economic framework conditions) for different values of the time horizon u and the C-emission reduction potential of bioenergy. It can be seen that there are still clearly delineated zones. The Pattern Map that was described in the previous section can be found, but it is sensitive to both, u and ϵ_L. This sensitivity has visible trends:

a reduction of ϵ_L causes an extension of the Pattern I-zone into the Pattern II-zone (Figure 4.3 a-d). A decrease of ϵ_L and an increase of u cause an extension of the Pattern I - zone into the Pattern II and Pattern III-zones (Figure 4.3 h and j-p). Only the minimum extent of Response Pattern I does not change at the different parameter constellations.

Lets start to read the graph at the top row (a-d). When ΔC^{Atm} is measured after a very small time horizon, and bioenergy has no potential to to reduce C-emissions ($\epsilon_L = 0$), only two response patterns are found (Pattern I and Pattern III). The trade-off Pattern II can not be found at $\epsilon_L = 0$. The reason is that, after the Pattern II-specific peak in emissions, there is no decrease of ΔC^{Atm}. In this extreme case, bioenergy has an adverse climate effect as soon as one fallow cell is converted, because there no emission reductions to compensate for the emissions from land use change.
The second and third row show results for low and medium ϵ_L (Figure 4.3 e-l). The known Pattern Map is found when the time horizon u is short. Measurements after longer u (Figure 4.3 h,l,p) yield a Pattern Map where only Pattern I is found. This means that bioenergy meets the goal of climate change mitigation, irrespective of the economic framework conditions and therefore irrespective of the conversion of fallow cells. The reason is that the C-emission reduction through bioenergy is effective enough to compensate for the C-emissions through the destruction of terrestrial C-stocks. In these cases the effect of the introduction of bioenergy on ΔC^{Atm} is independent of the ecosystem C-stocks and the economic framework conditions that determine the land use change.
The next step of our nested sensitivity analysis is to take a closer look at the influence of the ecological framework conditions.

4.3.4. The influence of the ecological conditions on the Pattern Maps

Figure 4.4 shows the sensitivity of the Pattern Maps to the maximum C-sequestration rate ψ and the maximum C-stock of a cell θ_{Max} at constant u and ϵ_L. It can be seen that the Pattern Maps are robust to changes in ψ. In contrast, they are sensitive to changes in θ_{Max}. It can be seen in Figure 4.4 that an increase of θ_{Max} leads to the emergence of the critical Response Patterns II and III.
This effect of θ_{max} for the occurrence of these patterns is further illustrated in Figure 4.5. It shows ΔC^{Atm} vs. D^{BE} at different θ_{max}. Evidently, θ_{max} drives the emergence of a trade-off pattern and an increase of ΔC^{Atm} until a critical value when all fallow cells are converted. The reason is that an increase in θ_{Max} is correlated with more climate damage through the introduction of bioenergy, because larger terrestrial C-stocks are being destroyed.

In contrast to θ_{Max}, the maximum C-sequestration rate ψ has no effect on the climate mitigation performance of bioenergy. This can be explained by the model dynamics and initialization. The C-sequestration rate is only effective when there are terrestrial C-stocks that are still growing and thus sequestering C. However, all the C-stocks in the system are initialized as “mature” C-stocks that hold θ_{max}. In the

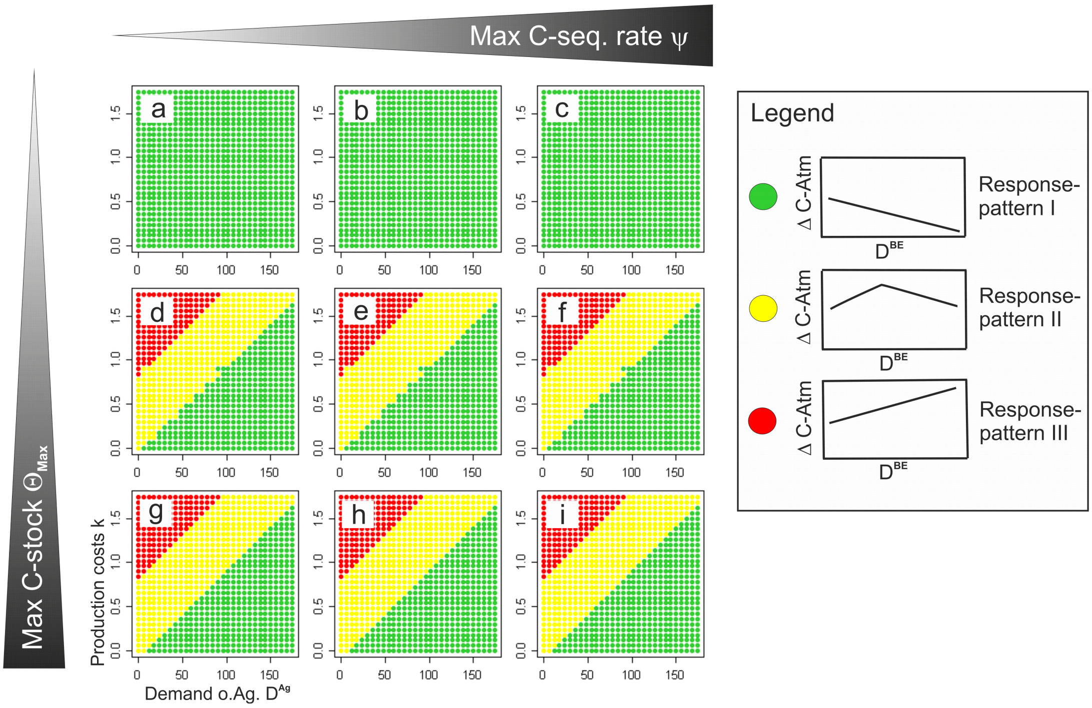

Figure 4.4.: Simulation results measured 50 years after the introduction of a demand for bioenergy. Parameters values: see Table 4.1, $\epsilon_L = -2$.

simulations no new C-stocks are created, because there is no incentive for the agents to change their land use in terms of giving up production. So the potential of the ecosystem to sequester carbon is irrelevant in this setting.
According to the strategy of our analysis the last step is a full understanding of the mechanisms that underly the observations which we described in the last two sections. This is accomplished in the following.

4.3.5. Untangling the interplay between the economic framework conditions, the potential of bioenergy to reduce C-emissions, the time horizon and the ecological framework conditions

As a first approach to understand the observations that we described in the previous sections in more detail we go back to simulation results from single runs for a parameter constellation. The goal is to analyze the transition from Pattern II or Pattern III to Pattern I, because this will allow to describe the conditions that lead to successful climate-change mitigation by bioenergy.

Figure 4.6 shows the response of ΔC^{Atm} to (D^{BE}) at different values of ϵ_L. It can be seen in Figure 4.6 (a) that a decrease in ϵ_L causes a decline of the curves‘ slope, but preserves the monotonicity. An intermediate trade-off response is absent. This indicates a lack of Response Pattern II and an immediate transition from Pattern III

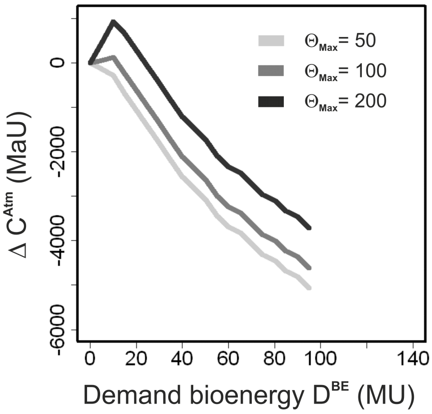

Figure 4.5.: ΔC^{Atm} vs. D^{BE} at different values for θ_{max}. A transition from Response Pattern II at high θ_{max} to Response Pattern II at low θ_{max} can be observed.

to Pattern I. This matches the observation that the extent of the zone for Pattern II is unchanged in the Pattern Maps (Pattern II is either absent or present).
With respect to the transition from Pattern II to Pattern I (Figure 4.6 b) it is noteworthy that the position of the inflection point remains unchanged. Before the point the transition resembles the shift from Pattern III to Pattern I.

This shows that the key to describe the threshold for the change from Pattern II or III to Pattern I is to understand which conditions lead to a change of the slope of the response curve in a situation where there are still fallow cells in the system. Again, we use analytical considerations as a tool to understand these observations. The approach is to express ΔC^{Atm} as a function of the economic, ecological and technological parameters in order to learn about the functional relationship between them. Two results from the previous Chapter 3 are used:

1. $H^{BE*} = \frac{D^{BE}}{k+TC}$

2. $H^{Fa*} = N - H^{Ag*} - H^{BE*}$.

This can be inserted in equation 4.4. For a time horizon u, we get:

$$\Delta C^{Atm} = C^{Atm}(D^{BE} > 0) - C^{Atm}(D^{BE} = 0)$$

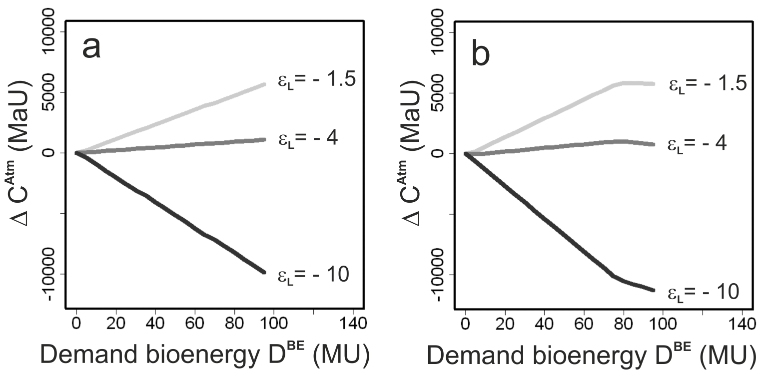

Figure 4.6.: Transition of Pattern III (left) and Pattern II (right) to Pattern I as an effect of an increase of the potential of bioenergy to reduce C-emissions (ϵ_L).

Therefore:

$$\begin{aligned}\Delta C^{Atm} &= -\left(N - H^{Ag*} - \frac{D^{BE}}{k+TC} - H^{Fa*}(D^{BE}=0)\right) \cdot \Delta\theta_{Min\to Max} \\ &\qquad + H^{Ag*} \cdot u \cdot e^{Ag} + \frac{D^{BE}}{k+TC} \cdot u \cdot (e^{BE} + \epsilon_L) \\ &= \frac{D^{BE}}{k+TC} \underbrace{\left[\Delta\theta_{Min\to Max} + \left(\epsilon_L + e^{BE}\right) \cdot u\right]}_{\lambda} + H^{Ag*} \cdot u \cdot e^{Ag}\end{aligned} \tag{4.5}$$

$\Delta\theta_{Min\to Max}$ denotes the difference between the maximum and the minimum C-stock of a cell, because this amount is released to the atmosphere when the cell is converted. The equation that describes ΔC^{Atm} consists of a part that is a factor of $D^{BE}(\lambda)$ and of a part that is constant with respect to changing bioenergy demands (remember that this equation describes the case $H^{Fa*} > 0$, so H^{Ag} is not influenced by changes in D^{BE}). The term λ determines whether the slope of the relationship between ΔC^{Atm} and D^{BE} is positive or negative. It includes the ecological and the technological framework conditions as well as the time horizon.
When λ is negative, a further D^{BE}-increase will lead to a decrease in ΔC^{Atm} and therefore to Response Pattern I. When λ is positive, a higher bioenergy demand will lead to higher ΔC^{Atm}.

The explicit formulation of the term λ can be further utilized to find out for which ϵ_L, u and $\Delta\theta_i$ the C^{Atm} response pattern becomes decoupled from the economic framework conditions. The condition for an increase in D^{BE} to have a beneficial climate mitigation effect is:

$$\lambda = \Delta\theta_{Min\to Max} + (e^{BE} + \epsilon_L) \cdot u < 0 \tag{4.6}$$

The fulfillment condition will lead to the emergence of Response Pattern I regardless of the economic conditions D^{Ag}, k and TC. It can be transformed to a number of equivalent conditions:

1. Time threshold:

$$u < \frac{\Delta\theta_{Min \to Max}}{-(e^{BE} + \epsilon_L)} \tag{4.7}$$

2. Technological threshold:

$$-\epsilon_L > \frac{\Delta\theta_{Min \to Max}}{u} + e^{BE} \tag{4.8}$$

3. Ecological threshold:

$$\Delta\theta_{Min \to Max} < u \cdot (-\epsilon_L - e^{BE}) \tag{4.9}$$

This exercise shows that Pattern I can be present and robust against a variation of the economic conditions only when the ecological, technological and time-conditions fulfill some minimum requirements. Only in these cases the introduction of bioenergy is beneficial for the climate (i.e. without unwanted side-effects). In all other cases the Patterns II and III can emerge, which means that there is a need for counteraction.

The functional relationships between the ecological framework conditions, the economic framework conditions and the time horizons are now explicitly named. This allows to describe the framework conditions under which bioenergy will meet the goal of climate change mitigation precisely.

4.4. Discussion

The objective of this chapter was to assess the effectiveness of bioenergy as a measure of climate change mitigation. This included the identification of side effects on the climate balance that are a consequence of the induced land use change. We found that various climate effects can be observed as a system response to an increasing bioenergy demand. Depending on the framework conditions bioenergy may miss or reach the goal of climate change mitigation.
This means that there may be the need for additional policy reaction in order to meet the goal of climate change mitigation. Situations where the introduction of bioenergy poses a climate-risk are characterized by a low potential of bioenergy to reduce C-emissions and/or much carbon that is stored in the ecosystem of the region.
Another main finding was the identification of an important trade-off between climate change mitigation by land use intensive technological means (like bioenergy production) and climate change mitigation by ecosystem services (like C-storage and sequestration). In the following sections we will discuss these findings in the context of the

current debate and formulate implications for the assessment and the governance of bioenergy.

4.4.1. Intended and unintended effects of an increasing bioenergy demand on the climate

We showed that the climate balance can exhibit three response patterns to an increasing bioenergy demand. These patterns have different implications concerning the need for action if the goal of climate change mitigation is to be achieved. Response Pattern I is characterized by a decrease of ΔC^{Atm}. In this case there is no need for action, because bioenergy meets the goal of climate change mitigation. Situations in which Pattern II (trade-off pattern) and Pattern III (increase of ΔC^{Atm}) emerge need further attention, because there is the risk that the goal of climate change mitigation is missed.

What are the reasons that bioenergy misses the goal of climate change mitigation? A prerequisite is that the region comprises areas that are not under cultivation. These can act as ecosystem C-stocks, which are at risk of being destroyed when additional pressure on the land use system occurs.
It has to be kept in mind that the processes which determine C^{Atm} differ in their temporal dynamics. The emissions from the conversion of fallow cells accrue once, when a terrestrial C-stock is destroyed. In contrast, the emission reduction by bioenergy is a rate (emission reduction per year). It takes place continuously. The emissions from land use change have been interpreted as a "carbon debt", that bioenergy has to "pay off" before it becomes a measure of climate change mitigation (Fargione et al., 2008, Achten and Verchot, 2011, Gelfand et al., 2011).
In our model, the need for additional policy action arises when bioenergy can not pay off its carbon debt during the chosen reference period.
Therefore, there is no need for action in cases that are characterized by a high potential of bioenergy to reduce C-emissions, by low ecosystem C-stocks or when long time horizons are considered. Accordingly, the introduction of bioenergy can have a positive climate effect, although it leads to the destruction of all ecosystem C-stocks as long as ϵ_L is high enough.
However, it is widely acknowledged that areas that are not under cultivation have more functions than C-storage and sequestration. Examples include conservation of biodiversity, important services concerning the water cycle or cultural and spiritual value (MA, 2005, Sukhdev et al., 2010). This highlights the importance of the choice of perspective when land use patterns are evaluated. When the analysis is extended by other criteria, different trade-offs apply.

How can these findings be translated to the real world? The maximum C-stock (θ_{Max}) is a property of the ecosystem. The properties of the vegetation to store carbon differ globally between regions (e.g. Sitch et al., 2003). Therefore, the need for action at an increasing bioenergy demand is regionally specific. In regions with a high potential of the vegetation to store carbon, e.g. rain forests, the risk is particularly

high, when bioenergy is introduced.
The interpretation of ϵ_L and its impacts is less straightforward. The parameter is defined as the property of bioenergy to substitute fossil fuels. It is highly aggregate, because it comprises characteristics within the land use system as well as outside the system boundaries. Inside the land use system, it is influenced by the choice and quality of the energy crops that are used as bioenergy feedstock (Sterner and Fritsche, 2011). Features of the production chain, like the use of byproducts, are of importance as well. Outside the land use system, it is relevant which fossil fuels are substituted by bioenergy (Cherubini et al., 2009, Cherubini and Strømman, 2011). This depends on the characteristics of the energy system in the region where the bioenergy is used. This shows that ϵ_L subsumes all the emissions along the entire life cycle of the energy crops.

4.4.2. What policy options exist when there is a need for action?

Bioenergy is often fostered by policies that create a demand, for example in the form of a blending quota for liquid fuels. This demand can be a driver of land use change. Our results indicate that this driver-based approach may result in a failure to meet the goal of climate change mitigation.
The economic, technological and ecological framework conditions determine the climate effect of an increasing demand for bioenergy. It is reasonable to assume that particularly the economic and ecological framework conditions are regionally distinct. Therefore, we propose that policies which take regional conditions into account are more likely to reach the goal of climate change mitigation than instruments that are less specific.
An important requirement for good governance is the option to readjust policies. The promotion of bioenergy by an increase in demand hardly meets this criterion. A lowering of the demand after C-stocks have been destroyed would be useless and counterproductive. The reason is that it would lead to a decrease of bioenergy production. This means that the time horizon that is needed until the C-debt is repaid increases.

Our model results also indicate that a cap on the demand for bioenergy is not an option to mitigate negative side effects of the introduction of bioenergy. While a cap on D^{BE} would limit the number of C-stocks that are destroyed, it would not influence the time after which the C-debt is paid off. Although the total C^{Atm} would be lower the goal of climate change mitigation would still be missed, because C^{Atm} is higher than the reference scenario without bioenergy.
It has to be kept in mind though, that the model reaches the market equilibrium quickly. The real world may be in a transitory state towards a market equilibrium (Tesfatsion, 2006, Arthur, 2006), hence lowering the bioenergy demand can be an option to reduce the pressure on the land use system.
An additional insight was that the potential of bioenergy to reduce C-emissions is crucial. This shows the need for policy instruments that discriminate between different bioenergy pathways (Tilman et al., 2009, Witcover et al., 2013).

However, there is also another conceivable governance option to lower the risk of unwanted side effects of bioenergy production. This is to employ additional, regionally optimized policy instruments with the specific goal to tackle side effects that can be expected.

4.4.3. Some general remarks concerning the methodology

A major outcome of this study are insights into the side-effects of fostering bioenergy on the climate balance. In addition, we learned about the factors controlling their emergence. We found that a complex interplay of economic, technological and ecological conditions are responsible.This could only be revealed, because the applied model enabled an explicit variation of the factors and an analysis of combined effects. Another feature was the nested sensitivity analysis and the use of "Response Patterns" and "Pattern Maps" in order to focus on differences in the qualitative system response.
In this study the usefulness of a model design that allows for analytical considerations became obvious at several occasions. We used analytical tools that we developed in Chapter 3 to test whether we had understood the correlation between the economic framework conditions and the response patterns correctly. This was conducted by formulating an hypothesis regarding the parameter space where a certain response pattern is to be expected. It was possible to express this formally and to validate it by comparison with simulation results. The formulations also pinpointed to another parameter that determines the climate effect of bioenergy but has not been tested so far (the transformation costs TC).
In this chapter we also derived an equation to calculate the atmospheric C-stock from insights we had gained so far about the behavior of the simulation model. This was later used to analyze the coupling of the land use patterns to the climate impact of bioenergy. The analytical considerations revealed how the relevant parameters functionally relate to the system response. The trade-off between the conservation of terrestrial C-stocks and the potential of bioenergy to to reduce C-emissions can be explicitly written down.

4.4.4. Conclusion and next steps

We have shown in this chapter that there are settings where the need for policy action arises, because there is the risk of unwanted climate side effects by bioenergy. These situations occur when there are many and/or particularly large C-stocks in the region. The risk increases when bioenergy is not reducing C-emission efficiently.
We have also learned that regional economic and ecological framework conditions are important. The next step will be to test whether the additional implementation of regionally optimized policy instruments can be an option to guarantee that bioenergy meets the goal of climate change mitigation.

5. Study II: Assessing the potential of policy instruments to combat unwanted side effects of bioenergy production

5.1. Introduction

In the last chapter we have seen that an increasing bioenergy demand can have unwanted side effects on the climate. Depending on the economical, ecological and technological framework conditions, an increase of the atmospheric C-stock can take place (instead of the intended decrease). The reason are C-emissions from the destruction of terrestrial C-stocks that can not be compensated for by the C-emission reduction through bioenergy. However, bioenergy is still seen as a possible solution for multiple challenges (Gamborg et al., 2012). Therefore, the question emerges whether potential climate side effects can be mitigated in order to enable a sustainable bioenergy production.

One idea, that has been brought forward, is the use of additional economic policy instruments to mitigate unwanted side effects through the land use change that is triggered by an increasing bioenergy demand (Killeen et al., 2011, Witcover et al., 2013). The proposed instruments aim to influence the land use decisions. Instruments with the goal of climate change mitigation should therefore set financial incentives for the land users to engage in (or refrain from) actions that influence the climate balance. Several strategies are possible to target different aspects of land use and its impacts:

1. Stopping the formation of new C-emission sources by avoiding the destruction of ecosystem C-stocks
2. Fostering the creation of additional C-sinks by creating new ecosystem C-stocks
3. Avoiding permanent C-emissions
4. Fostering a decrease of the permanent C-emissions

Policy instruments can be designed from these strategies by setting positive or negative economic incentives in order to motivate behavior that is in line with them.

Our goal is now to identify policy instruments that effectively mitigate potential climate side effects of bioenergy production. To achieve this goal the instruments need to be tested in combination with a bioenergy demand. This incentive from the market

is widely discussed to interfere with the performance of policy instruments that target land use decisions (Butler et al., 2009, Corbera and Schroeder, 2011, Barua et al., 2012, Busch et al., 2012, Persson, 2012). Our model allows for testing the outcomes of an interplay of both of these drivers.
In addition, the question arises whether the performance of the instruments is robust to changing ecological and technological framework conditions. Our model allows to test for variations of these conditions. The insights can be used to learn about potential regionally adapted policy mixes.

However, a specific challenge emerges when additional policy instruments are applied: they may lead to a decline of the areas that are under cultivation. An instrument can, for example, foster the creation of a new C-stock on areas that had been used for agricultural production before (Ghazoul et al., 2010, Lambin and Meyfroidt, 2011, Smith et al., 2013). This may lead to a reduction of the added value that is generated in the region (e.g. through a reduction of the harvests). Therefore, it also impedes one of the strategic goals of bioenergy production (i.e. added value generation in rural areas).
One way out of this goal conflict is to define a maximum tolerated extent of the side effect while optimizing with respect to the desired goal. We use this approach in order to deal with the trade-off.

5.2. Methods

5.2.1. Policy instruments used

In this analysis we use the modeling framework that is described in Chapter 2. However, in contrast to the preceding chapters the policy instruments are switched on. Table 5.1 gives an overview over the different types of the tested economic instruments. A detailed specification of the submodels can be found in Chapter 2. The design of the instruments relates to the climate change mitigation strategies that were identified in the previous section. The power of the instrument is regulated by the parameter τ (incentive rate) in combination with characteristics of the emission or emission reduction (e.g. the size of the C-stock for I 1, I 2 and I 3). We use τ for optimizing the policy instruments in the following analysis.

Table 5.1.: Overview of the policy instruments

Instrument	**Climate change mitigation strategy and functioning**
I 1: Tax C-stock	Strategy 1: Agent has to pay for C-emissions when it destroys an ecosystem C-stock.
I 2: Payment C-stock	Strategies 1 and 2: Agent obtains a payment for the ecosystem C-stock on its cell in every time-step.
I 3: Mix I 1 and I 2	Strategies 1 and 2: Agent obtains a payment for the ecosystem C-stock on its cell in every time step. When it destroys the C-stock, it has to pay for the C-emissions.
I 4: Payment C-seq	Strategies 4 and 1: Agent obtains a payment for the C-sequestration by its cell in every time step.
I 5: Tax emission	Strategy 3: Agent has to pay for all C-emissions from its land use (emissions from land use change, emissions from land use), the emission reduction by bioenergy is considered.
I 6: Payment emission red	Strategy 4: Agent obtains a payment for C-reduction from its land use (by emission reduction through bioenergy or C-sequestration by the vegetation).

5.2.2. Assessing the effectiveness of the policy instruments

The goal of this study is to compare different designs of policy instruments. The target of the instruments is climate protection. Therefore their success is measured by the reduction of atmospheric C-stock (λ_C) that they can achieve under different framework conditions. However, the use of the policy instruments can lead to a reduction of areas under cultivation. Figure 5.1 illustrates this trade-off. It shows the effect of a policy instrument measured with respect to its climate change mitigation performance and its socio-economic side effect. The stronger the incentive of the instrument is, the more climate change mitigation can be achieved. However, an increasing strength of the incentive leads to a greater loss of cells under cultivation (i.e. socio economic side effect).

We define the performance measure of the incentive as the relative reduction of the atmospheric C-stock C^{Atm} through the instrument (^{U} is the simulation result without the instrument, ^{I} is the simulation result with the instrument):

$$\lambda_C = \frac{C^{Atm,U} - C^{Atm,I}}{C^{Atm,U}} \tag{5.1}$$

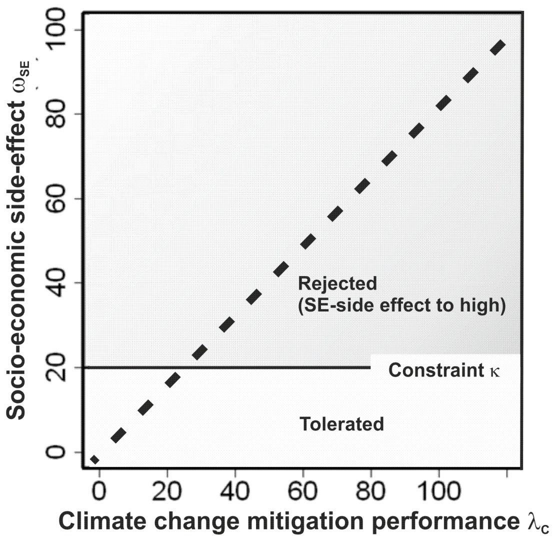

Figure 5.1.: Trade-off between climate change mitigation performance and socio-economic side effect of an instrument. The dashed line indicates outcomes for a policy instrument measured with respect to the two evaluation criteria.

We define the extent of the socio-economic side effect as the relative reduction of cells that are under cultivation through the instrument:

$$\omega_{SE} = \frac{(H^{Ag,U} + H^{BE,U}) - (H^{Ag,I} + H^{BE,I})}{(H^{Ag,U} + H^{BE,U})} \tag{5.2}$$

Our optimization aims to maximize the performance of the instrument under the constraint that the extent of the side effect remains below a defined value κ:

$$\lambda_C(\tau) \xrightarrow{\tau} Max!$$
$$\text{under the constraint: } \omega_{SE}(\tau) \leq \kappa$$

The analysis consists of two steps:

1. Optimization of the strength of the instrument τ at a particular demand for bioenergy D^{BE} and for various tested parameter constellations

2. Comparative assessment of the performance of the optimized policy instruments under different framework conditions

We use the insights about the need for policy action from Chapter 4 to chose a parameter constellation which leads to response Pattern II (i.e. partial need for policy action). The performance of the optimized instruments is measured by a comparison of C^{Atm} vs. D^{BE} with an instrument against C^{Atm} vs. D^{BE} without an instrument.

In order to test for the ecological and technological framework conditions, we varied the maximum C-sequestration rate (ψ), the maximum C-storage capacity of a cell (θ_{Max} at constant θ_{Min})) and the potential of bioenergy to reduce C-emissions (ϵ_L). In the last part of the analysis we assess the influence of the optimization constraint κ (i.e. the maximum tolerated socio-economic side-effect). An overview over the tested parameter ranges is shown in Table 5.2.

Table 5.2.: Parameter values of the model

Symbol	**Connotation**	**Value**	**Unit**
N	Number of agents	100	–
D^{Ag}	Demand for other agrarian products	40	Money units [1]
D^{BE}	Demand for bioenergy	[0,5,10,...,100]	Money units
k	Production costs	0.8	Money units
TC	Costs for changing production	0.1	Money units
θ_{Max}	Maximum C-stock of a cell	[100,200]	Mass units [2]
θ_{Min}	Minimum C-stock of a cell	10	Mass units
ψ	Maximum C-sequestration rate of a cell	[0.1,0.2,0.3]	Mass units
$e_i^j(t)$	C-emission of a cell through the production of j	1	Mass units
u	Time horizon	50	Years
ε_L	C-emission reduction by bioenergy during its life cycle	[-2,-10,-20]	Mass units
τ	Incentive rate	[0.000,0.002,...,0.8]	Money units per Mass unit

[1] abbreviated as MU in the following,
[2] abbreviated as MaU in the following

5.3. Results

5.3.1. Step one: Choosing optimal tax rates

In this steps we show how the optimal incentive rates τ^* were chosen. Figure 5.2 shows results for the climate performance λ_C and the socio-economic side effect ω_{SE} at different incentive rates τ for one exemplary parameter constellation. λ_C and ω_{SE} increase with increasing τ. The shape of the trade-off curves differs between the instruments and depends on the parameter constellation. It can be seen that the trade-off cost curves for the instruments I 1 (Tax C-stock), I 2 (Payment C-stock), I 3 (Mix I 1 and I 2) and I 5 (Tax on the emissions) are linear. These instruments have in common that the amount of their incentive is based on the C-stock. In contrast, the shape of the trade-off curve is more complex for the emission-based instruments I 4 (Payment C-seq.) and I 6 (Payment emission red.).

The incentive rates that are chosen at a maximum tolerated socio-economic side effect $\kappa = 20$ are marked with an asterisk. One striking observation is that the amount of the optimal incentive rate differs considerably between the different types of instruments. The τ^* for I 1, I 2, I 3 and I 5 are much lower than for I 4 and I 6. This can be explained by the different designs of the instruments: the amount of the incentive of the instruments with small τ^* is coupled to the the maximum C-stock θ_{Max}. In the chosen parameter constellation this is relatively high (θ_{Max}=100). Consequently already small τ lead to ω_{SE} that are higher than κ. In contrast, for I 4 and I 6 κ is reached at high τ^*. These instruments function by setting an incentive for emission reduction through sequestration of the ecosystem C-stock and through technological means. At the given example for a parameter constellation these are comparatively small. Therefore the instruments require higher τ.

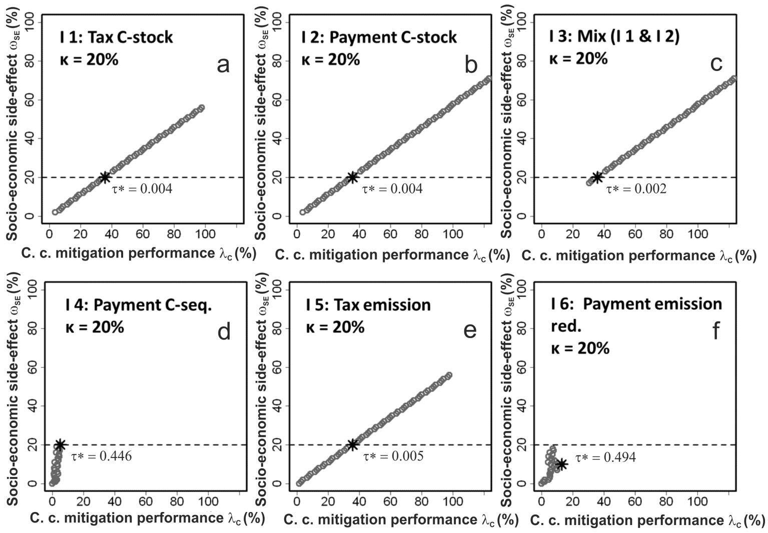

Figure 5.2.: Choice of the optimal tax rate τ^* at one parameter constellation for one D^{BE}-value. The dashed line indicates κ. The black asterisk indicates the value that was chosen and then used for the simulation to assess the performance of the different policy instruments. Parameter values: $D^{Ag} = 40$ MU,$D^{BE} = 70$ MU, $c^j = 0.8$ MU, $TC = 0.1$ MU, $e^{Ag} = e^{BE} = 1$ MaU, $\epsilon_L = -2$ MaU, $\theta_{Max} = 100$ MaU, $\psi = 0.3$ MaU, $\theta_{Min} = 10$ MaU, $u = 50$Y

5.3.2. Step two: Comparing the performance of the optimized policy instruments under different framework conditions

In the second step of the analysis, the performance of the optimized instruments is assessed for different ecological and technological framework conditions. Our goal is to determine the ranking order between the instrument types and to test whether the results are robust to variations of the conditions.

Performance of the instruments under variable ecological conditions

Figure 5.3 shows results for variable maximum C-storage capacities of a cell (θ_{Max}) and maximum C-sequestration rate (ψ) at an increasing bioenergy demand D^{BE}.
It can be seen that ranges of D^{BE} exist where the instruments differ in their performance. However, there are also D^{BE}-ranges where all tested instrument types have the same effect. This observation is different between low and high θ_{Max}. For low values of θ_{Max} (Fig. 5.3 a-c) there is a critical demand for bioenergy (at $D^{BE} \approx 50$), below which all instruments behave identically quantitatively and qualitatively (i.e. their effectiveness slightly increases with an increase of D^{BE}). Above the critical value, two groups of instruments can be distinguished. Group One consists of I 1, I 2, I 3, and I 5 and is more effective than the Group Two (which consists of I 4 and I 6). Group One instruments remain effective with increasing D^{BE}, whereas Group Two instruments loose their effectiveness. The reason is that the incentive that is set by these instruments is to small to compete with the incentive from the high bioenergy demand. This is in line with the results from the previous section, that demonstrated that instruments which are sequestration-based may require high τ.
At θ_{Max} (Figure 5.3 d-f), there are also ranges where the instruments do not differ in their performance. With increasing ψ-values the differentiation into two instrument groups can be observed as well. However, there is no critical D^{BE} value above which the Group Two instruments become ineffective (they become ineffective for the whole range of D^{BE} values).

The functional response to an increase of ψ also differs for different θ_{Max}. At low θ_{Max} (Figure 5.3 a-c) the performance of all instruments is insensitive to ψ. In contrast, at high θ_{Max}, the different instrument groups show different reactions. Group One instruments are insensitive to ψ, whereas for Group Two instruments they are not. The reason for this observation is that the instruments have different impacts on the land use system. The effectiveness of the Group One instruments is caused by the conservation of a share of existing C-stocks. This mechanism is insensitive to sequestration rates. Group Two instruments have in common that their incentive is coupled to the C-sequestration. However, amazingly the performance of these instruments diminishes with increasing ψ. The reason is that they set an incentive to create new C-stocks, but do not protect old C-stocks (which sequester no or little carbon). The instruments effectively cause some agents to exit the market and convert their cells into C-stocks. This leads to a decrease of the regional supplies which causes increasing prices. Therefore, it becomes profitable to convert old C-stocks for the production of bioenergy or other agricultural goods. The carbon that is stored in them is released to the atmosphere, which causes the instrument to be less effective than the instruments that protect old C-stocks.

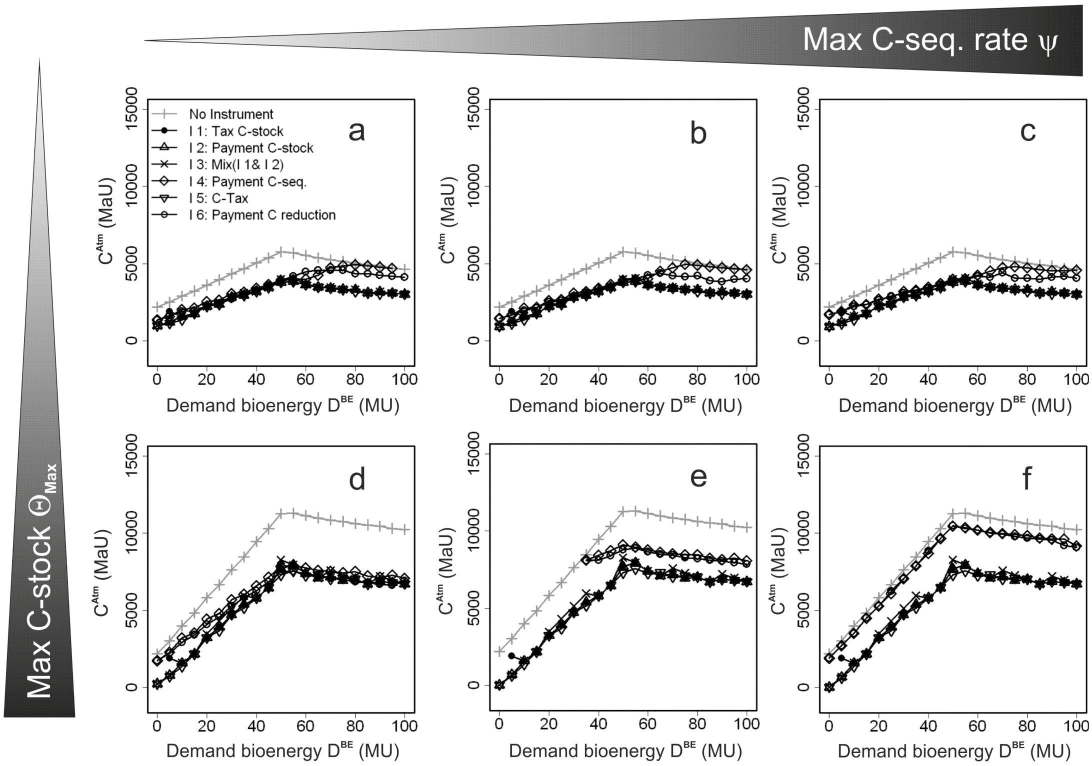

Figure 5.3.: Effect of differently designed policy instruments on C^{Atm} compared to increasing D^{BE} without additional instruments. Dots were omitted when no τ^* was found. Parameters values: see Table 5.2, $\epsilon_L = -2$ MaU

Performance of the instruments under variable technological conditions

In addition to testing for ecological framework conditions, we analyzed the performance of the instruments at various potentials of bioenergy to reduce C-emissions (ϵ_L). Figure 5.4 shows the performance of the different optimized instruments for an increasing bioenergy demand D^{BE} and increasing values of ϵ_L.
It is a striking result that most of the instruments are rather ineffective (i.e. hardly any reduction of C^{Atm} through the instrument). This is an effect of testing the instruments in combination with bioenergy-production as another measure of climate change mitigation. When bioenergy is very effectively reducing C^{Atm}, additional policy instruments that impede bioenergy cultivation may not be useful from the perspective of climate change mitigation. Note that with an increase of ϵ_L the Response Pattern changes towards the intended Pattern I (i.e. no unwanted climate side effect, cf. Chapter 4).
The combined effect of policy instruments and climate change mitigation through bioenergy is illustrated further in Figure 5.4 (d-f). The graphs show the effectiveness of the instruments at an increasing incentive rate τ. The bioenergy demand D^{BE} is kept fixed. When ϵ_L is small (Figure 5.4 d), an increase of τ leads to a decrease of C^{Atm}. In contrast, at higher ϵ_L an increase of τ has the opposite effect for most of the instruments (i.e. an increase of C^{Atm}, Figure 5.4 e-f). This means that most of the instruments lead to a less desirable outcome than in a situation without the instrument. In these cases climate change mitigation is primarily caused by the potential of bioenergy to reduce C-emissions ϵ_L and not by the conservation of ecosystem C-stocks. Therefore, the instruments that foster ecosystem C-stocks become counterproductive.
An exception from these observations is the payment for C-reduction (I 6). It becomes more effective when the potential of bioenergy to reduce C-emissions increases. The reason is that it comprises an incentive to cultivate energy crops, because the emission reduction that this entails is rewarded. Hence, for this policy instrument, the trade-off between λ_C and ω_{SE} does not apply for some parameter constellations.
Figure 5.4 (g-i) shows the percentage of the different land use forms for the tested policy instruments at increasing ϵ_L and $D^{BE} = 15$. Instruments I 1,I 2,I 3 and I 5 lead to higher percentages of fallow cells at the expense of other agrarian production. The effect of I 6 differs and changes the land use pattern completely. When it is employed, the resulting region consists almost exclusively of bioenergy cultivation at medium or high ϵ_L. Under this framework conditions the application of the instrument leads to the destruction of all terrestrial C-stocks. In addition, the cultivation of other agrarian goods is much lower than in the reference scenario or when the other instruments are applied.

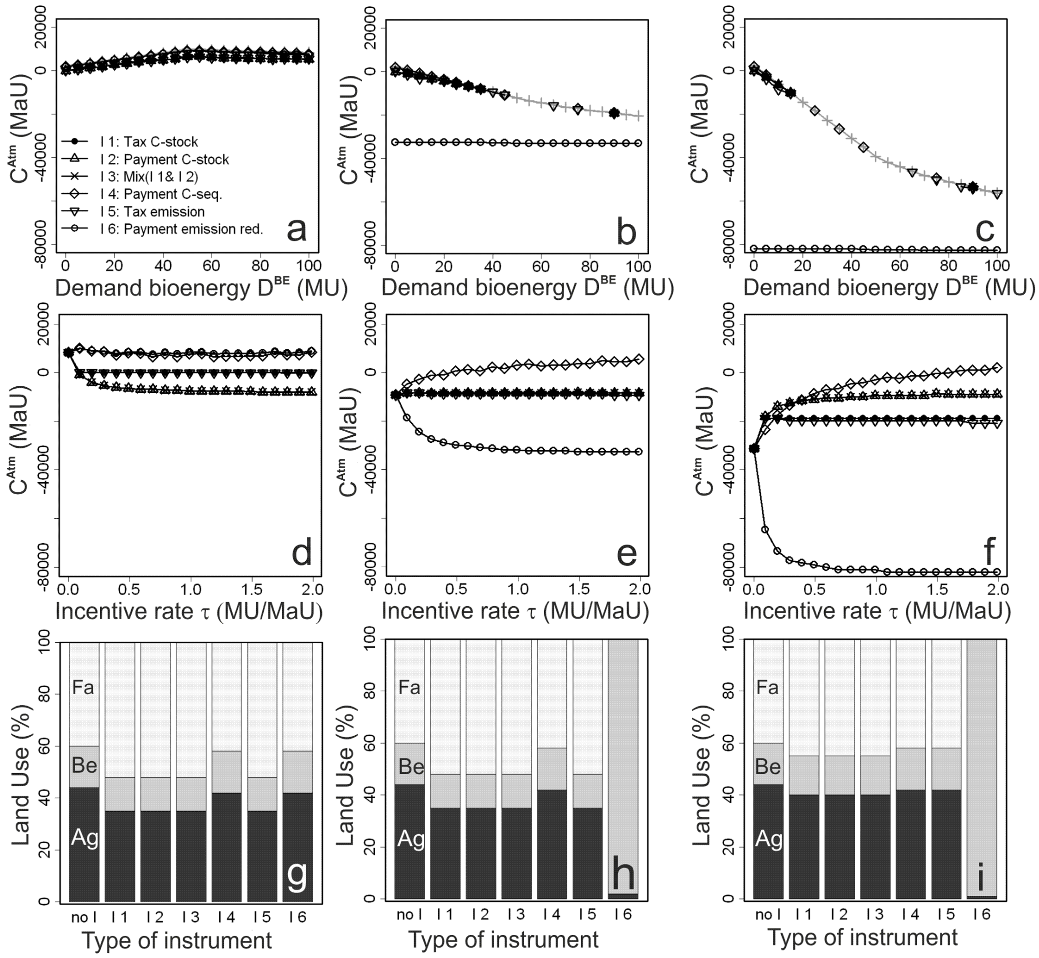

Figure 5.4.: Upper row: Performance of the instruments for different potentials of bioenergy to reduce C^{Atm}. Dots were omitted when no τ^* was found. Middle row: Influence of increasing incentive rates τ on the atmospheric C-stock for different values of ϵ_L. Lower row: Percentages of land use for the cultivation of bioenergy (BE), cultivation of other agrarian products (Ag) and no production/fallow land (Fa) at $D^{BE} = 15$ MU using τ^*. Other parameter values: $\theta_{Max} = 200$ MaU,$\psi = 0.3$ MaU

5.3.3. The effect of the maximum tolerated socio-economic side effect κ

In the last section of this chapter we analyze the influence of the optimization constraint κ on the achievable reduction in C^{Atm}. Remember that κ is defined as the maximum tolerated relative loss of area under cultivation (ω_{SE}). The higher κ, the more areas can be converted to fallow cells for climate protection. Figure 5.5 shows the performance of the policy instruments at increasing D^{BE} for tolerated reductions of $\kappa = 30$, 60 and 90 percent of area under cultivation.
At the lowest tested κ-value, the instruments are similar in their performance. This changes when κ increases: the performance of I 1 - I 3 and I 5 enhances, whereas the performance of I 4 and I 6 remains stable. At the highest κ value, the payment for the C-stock (I 2) and the mix of the tax and the payment (I 3) perform better than the tax on the conversion of C-stocks (I 1). The reason is that I 1 works exclusively by the conservation of old C-stocks. Its performance is limited by the amount of existing C-stocks. Therefore, an increase from medium to high κ is ineffective. The performance of instruments I 4 and I 6 (which are the Group Two instruments) can not be further improved when a higher socio-ecological side effect is tolerated. The incentive that they can set is limited by the C-stock that can be built up in one time step. This finding will be further discussed later.

Figure 5.6 shows the reduction of C^{Atm} by the policy instruments for different κ at one D^{BE}-value. For all instruments, an increase of the maximum tolerated socio-economic side effect leads to an increase in performance. However, this increase levels at an instrument-specific maximum reduction of atmospheric C-stock. This maximum reduction is determined by the different functionings of the instruments.
To conclude, the willingness to pay a higher price for climate change mitigation (in terms of maximum tolerated socio-economic side effect) may or may not lead to a better climate outcome, depending on the design of the policy instrument that is employed.

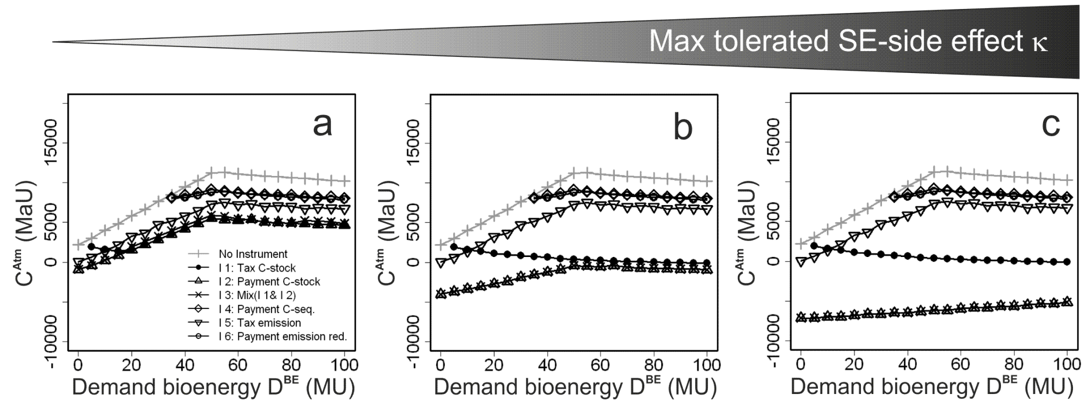

Figure 5.5.: Policy instruments Performance vs. D^{BE} at variable κ. Values are omitted when ($C^{Atm,U} = C^{Atm,I}$). Other parameter values: $\epsilon_L = -2$ MaU, $\theta_{Max} = 200$ MaU, $\psi = 0.3$ MaU

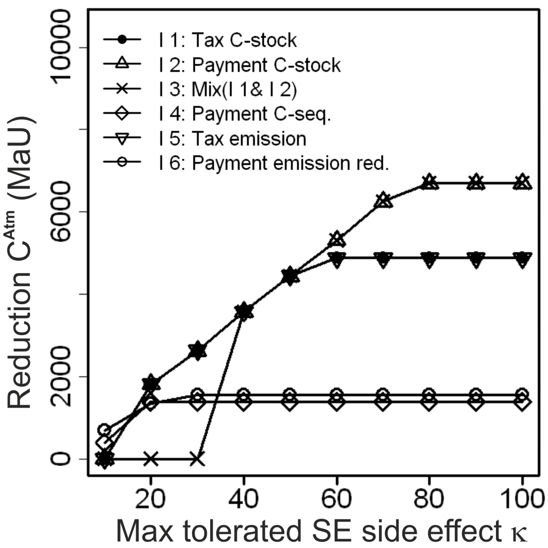

Figure 5.6.: Effect of the policy instruments at different values for the maximum tolerated socio-economic side effect κ.Other parameter values: $\epsilon_L = -2MaU$, $\theta_{Max} = 200MaU$, $\psi = 0.3MaU$, $D^{BE} = 15MU$

5.4. Discussion

In this chapter we tested the potential of differently designed, optimized policy instruments to mitigate unwanted side effects of bioenergy production on the climate. In most cases a reduction of the atmospheric C-stock C^{Atm} could be achieved with the tested policy instruments. However, it is important to keep in mind that this is a reduction relative to the introduction of bioenergy without additional policy instruments.

5.4.1. Lessons learned concerning the design and assessment of policy instruments

One important finding was that the climate performance of the different policy instruments can be independent of the specific details of the design. This can be explained by the fact that we compared optimized instruments. However, there are also cases where the design of the instrument matters, for example when the tolerance to socio-economic side effects, such as the loss of cells under cultivation, increases. This shows that the side effect on the climate caused by bioenergy production can be converted to a socio-economic side effect by the additional policy instruments.

Another finding was that there can be a trade-off between climate change mitigation by the conservation of ecosystem C-stocks and by the potential of bioenergy to reduce C-emissions (ϵ_L). In an idealized case with very high ϵ_L, the instruments may even counteract climate change mitigation, because they prevent areas from being used for bioenergy production. Although in reality extremely high ϵ_L may be unfeasible (Searchinger et al., 2009, Searchinger, 2010, Haberl, 2013), the combined effect that is caused by the hindrance of bioenergy production has to be taken into account when climate change mitigation instruments that affect land use are assessed.

However, areas which are not under cultivation have more functions than climate protection through C-storage and sequestration. Examples include other ecosystem services like water regulation and provision or the provision of food and raw materials (MA, 2005, Sukhdev et al., 2010). It is important to consider these explicitly when land use policies are designed, because a synergy with climate change mitigation is not necessarily given.

5.4.2. The results in the context of the current debate on REDD+

In this chapter, we evaluated both, hypothetical and existing policy instruments. The instruments which are designed as payments for ecosystem services, comprising I 2 (payment for the conservation ecosystem of C-stocks), I 4 (payment for C-sequestration) and the payment part of the mix instrument I 3, are inspired by an existent policy, the REDD mechanism. The acronym stands for reducing emissions from deforestation and forest degradation. The goal of the policy is to reduce the emissions from deforestation by financial incentives for developing countries (UNFCCC, 2005). It is currently intensively debated whether policies that implement REDD have the potential to counteract unwanted side effects of bioenergy production or are unattractive for land users before the background of an increasing bioenergy demand (Butler et al., 2009, Killeen et al., 2011, Barua et al., 2012, Busch et al., 2012, Persson, 2012). Our model results indicate that optimized REDD instruments could be promising, because the payment for the terrestrial C-stock is one of the most successful instruments for climate protection. Although its performance is influenced by the demand for bioenergy, it is still effective, even at a high D^{BE}.

In contrast, the instruments that set an incentive by a payment for C-sequestration are ineffective compared to the other instruments. This has two reasons. One reason is that in the current model the height of the incentive is determined by the C-stock that can be built up within *one* time step. More time is needed for a C-stock to grow to be profitable in comparison to the other land use options. This highlights the importance of accounting for the temporal dynamics of ecosystems when policies that reward them are designed. This includes the time span that the ecosystem requires until it can provide the service that is of interest for the society (in our example C-storage and C-sequestration). These delay effects have to be integrated in potential novel policy instruments. More generally, this is a part of the challenge of governing social-ecological systems, which may comprise "slow-," and "fast moving" variables (Janssen and Ostrom, 2006a).

The second reason for the low performance of the instruments which reward C-sequestration is that they lead to the destruction of old-growth C-stocks. This causes high emissions and is an example for a misguided incentive. Further investigation on whether this type of instrument can function or whether it is risky to employ it is needed. This is also highly relevant in the REDD debate where there is the concern that REDD-instruments could set an incentive to create fast growing C-stocks (like *Eucalytus* plantations) and thus have adverse indirect effects (Phelps et al., 2012).

It is important to keep in mind that for the analysis in this chapter only the effectiveness of climate change mitigation measures was considered. Solutions that are optimal from the point of view of climate protection may have adverse effects on other functions of land, like biodiversity conservation (Phelps et al., 2012). This is drastically shown in figure 5.4, where additionally politically fostering of bioenergy leads to a region where the land use almost exclusively consists of bioenergy production. In contrast, the instruments that set incentives to conserve terrestrial C-stocks have potentially beneficial side effects on biodiversity conservation, as terrestrial C-stocks as forests or peat land consist of many habitats.

To conclude, we found that additional policy instruments have the potential to mitigate unwanted climate side effects of bioenergy production. Their performance depends on the instrument design, the potential of bioenergy to reduce C-emissions

and (when the instruments require the protection of natural C-stocks) the willingness to devote areas under cultivation to the conservation of natural C-stocks.
However, we also found that these instruments can cause different unwanted side effects (in this case a socio-economic side-effect in the form of the loss of cells under cultivation). This forces the society to negotiate which side effect it is willing to tolerate to what extent.

Part III.

Methodological reflection

5.5. Introduction to Part III

The previous parts of this thesis were exclusively dedicated to the presentation of the original results of my own work (ie. the presentation of a modeling framework in Part I and two exemplary applications concerning aspects of bioenergy-driven land use change in Part II. However, it was also an integral part of my PhD-project to invest efforts in the development of the method of agent-based modeling (ABM) because this is a very promising approach for studies that require the integration of social and ecological aspects (Liu et al., 2007, Janssen and Ostrom, 2006a,b, Rounsevell and Arneth, 2011). This, however, was the work of an entire team (i.e. a cross-departmental journal club at the Helmholtz Centre for Environmental Research - UFZ) that was founded in 2010 and co-coordinated by me.
Subject of the journal club was “Modeling human decisions in the context of land use change”. Based on an ample literature survey concepts of systematization and methodological improvements have been developed. I have actively contributed to all steps of the work. Therefore this thesis comprises Part III with a different character, i.e. presenting two suggestions for a methodological improvement of ABM which emerged from the activities of the journal club. One of them has been already published, the other has been submitted. The aim of both contributions is an improvement of the documentation and communication of ABMs. In Chapter 6 we present a structured protocol which is an extension of the widely used ODD-protocol (Grimm et al., 2006, 2010). In Chapter 7 we give an overview over existent forms of model documentations for ABMs and discuss their suitability for different purposes.

6. Describing human decisions in agent-based models - ODD+D, an extension of the ODD protocol

This chapter is based on a joint publication:

Müller, B., Bohn, F., Dreßler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. and Schwarz, N. (2013). Describing human decisions in agent-based models - ODD + D, an extension of the ODD protocol. Environmental Modelling & Software 48, 37 - 48.

6.1. Introduction

It is widely acknowledged that process-based models, and in particular agent-based models (ABMs), can play an important role in fostering understanding of the dynamics of complex systems (see Matthews et al., 2007, Clifford, 2008, Polasky et al., 2011, Schlüeter et al., 2012, with respect to coupled human-environmental systems). A number of studies have demonstrated that the appropriate inclusion of human decision-making in models is of fundamental importance (Parker et al., 2003, Bousquet and Le Page, 2004, Jager and Mosler, 2007, Parker et al., 2008b, Le et al., 2012). This is supported by the fact that, in many modeling studies, macro-level patterns are strongly influenced by the assumed human decisions and behavior at the micro-level (Hare and Deadman, 2004, Rounsevell and Arneth, 2011). However, current modeling practice has two substantial shortcomings:

1. The reasoning behind the choice of a certain human decision model is often not well documented; insufficient empirical or theoretical foundations are given; or the decision model is only assumed on an ad-hoc basis (Feola and Binder, 2010).

2. Often the model is not described in a transparent manner (clear and complete) that would allow for reproducibility and facilitate the communication of the model and its results (Polhill et al., 2008).

Consequently, model comparison and advancement is hampered to a large extent. Referring to first shortcoming, one has to take into account that decision-making in ABMs can be based on various theories (for an introduction see Baron, 2000): A widely used approach for modeling decision-making in general, especially in economics, is rational-choice theory (Sen, 2008). However, rational-choice theory has been criticized for being overly simplistic (Camerer and Loewenstein, 2004). Various alternative theories of how

decision-making is in reality based on a more bounded rationality have been proposed (Simon, 2008, Kahneman, 2003, Gigerenzer and Selten, 2001). For implementation in ABMs, rational choice theory is often represented by an optimization routine, whereas models based on bounded rationality rely on condition-action rules or on a combination of both approaches (Schreinemachers and Berger, 2006). New opportunities to model bounded rationality are considered to be one of the major advantages of using an ABM approach (Epstein, 2006), and there are by now many examples of ABMs that make use of bounded rationality (Jager et al., 2000, Duffy, 2001, Pahl-Wostl and Ebenhöh, 2004).
Referring to the second shortcoming mentioned above, several attempts have been made in the social sciences and land-use sciences to develop frameworks, classification schemes or protocols to represent and communicate ABMs. Hare and Deadman (2004) presented a taxonomic structure to help modelers choose the appropriate model type based on three requirements for social-ecological ABMs: Different specifications for

1. the coupling of social and environmental models,

2. social interactions and

3. the intrinsic adaptation of the agents.

Richiardi et al. (2006) criticized the lack of a methodological standard for social ABMs and proposed a three-stage process that could lead to the establishment of such standards in social and economic simulations. The proposed process was based on the development of a questionnaire that includes specific questions on the model structure (including decision-making mechanisms), model analysis and replicability. According to the authors, the evaluation of the questionnaire can then provide the input for a methodological protocol. The MR POTATOHEAD framework, "Model Representing Potential Objects That Appear in The Ontology of Human-Environmental Actions & Decisions", represents key elements of standard ABM and LUCC (Land Use and Cover Change) models in a structured and comprehensive way (Parker et al., 2008b). This "conceptual design patter" aims first to facilitate a comparison of the structure and functioning of different models and second to assist scholars new to the field with designing their models. Certain facets of human decisions are discussed in all three of these classification schemes and frameworks. However, these studies differ in terms of purpose and none of them puts the main focus on human decisions or elaborates on this topic in a comprehensive way.

Modeling in general, not only the modeling of human decisions, has to address the challenge of providing transparent and complete model descriptions (Richiardi et al., 2006, Parker et al., 2008b). Standardized protocols for (agent-based) model descriptions and especially the ODD (Overview, Design Concepts and Details) protocol (Grimm et al., 2006, 2010) have been well received by the scientific community. The ODD protocol consists of three parts: First, it provides an "Overview" on the purpose and main processes of the model. Second, in the "Design Concepts" block, the general concepts underlying the model design are depicted and third, in the "Details", all of the necessary information is given that would allow for a reimplementation of the model. However, the original ODD protocol focuses primarily on ecological dynamics (Grimm et al., 2006). The first revision of the ODD protocol has attempted to open the standard for all ABMs (Grimm et al., 2010). Nevertheless, a comprehensive description of the human decision process was not a focal point until now.

First attempts have been made to determine the usefulness of the ODD protocol for describing social-ecological models. Polhill et al. (2008) investigated to which extent the ODD protocol can be applied to LUCC models, considering three ABMs that include human agents as examples. They concluded that the ODD protocol could provide a useful standard to facilitate communication and model comparison. However, refinements are required concerning the definition of terms (such as entities, state variables and parameters). An (2012) took the same line and concluded in his review on modeling and understanding human decisions that the development of protocols similar to the ODD protocol for social-ecological models aimed at modeling human decisions must be put on the future research agenda.

We want to address this gap. The aim of this paper is to provide an extension of the ODD protocol, termed ODD+D (ODD + Decision) which facilitates a clear and comprehensive description of ABMs in a standardized way, with an emphasis on human decisions and which includes the empirical and theoretical foundations for the choice of decision model. The paper is structured as follows: In the next section, the main shortcomings of the ODD protocol, in particular with respect to describing human decisions, are summarized. Then, important terms are defined. The terms decision-making, adaptation and learning are clarified and distinguished. Furthermore, general structural changes in the ODD+D protocol (mainly in the Design Concepts block), as compared to the ODD protocol, are delineated and discussed. Afterwards, we present a detailed description of the revised and new design concepts with an emphasis on human decision-making. In Section 4, we illustrate the application of the extended protocol ODD+D by describing a social-ecological ABM on water use as an example. Given our background in social-ecological modeling, we refer for illustrative purposes in Sections 3 and 4 to examples from that domain, but we believe that the ODD+D protocol may prove to be a helpful protocol for describing ABMs that include human decisions in general. The discussion section focuses on the expected benefits and the efforts required while applying the protocol. The section closes with open challenges for the future.

6.1.1. Shortcomings of the ODD protocol for describing human decision-making

The ODD protocol is not fully suited to describe how human decision-making has been modeled for the following reasons:

1) Central aspects of modeling human decision-making are not explicitly addressed, such as decision algorithms, the formation of expectation, the temporal characteristics

of decision-making and cultural values, amongst others. 2) The theoretical and empirical basis for the chosen decision submodel is not sufficiently emphasized. 3) The "Design concepts" section does not provide a suitable structure for describing human decision-making.

1. Central aspects of human decision-making are addressed in related frameworks: In their checklist-type summary, Richiardi et al. (2006) mention the type of agent behavior (optimizing, satisficing, . . .), the interaction structure, the coordination structure, the formation of expectations and learning with respect to decision-making. In their MR POTATOHEAD framework Parker et al. (2008b) use the decision algorithm of the agents, their characteristics and cultural values, and the temporal aspects in decision-making and the like as general aspects of decision-making. While the ODD protocol includes some of these aspects (e.g. interaction), other aspects such as coordination, the temporal aspects in decision-making and cultural values are not explicitly mentioned (see Table 1 Section II.ii of ODD+D).

2. Different scientific disciplines use a variety of approaches for conceptualizing human decision-making. Even within a single discipline, different schools of thought have specific, often implicit assumptions about decision-making. Without knowing the exact theoretical or conceptual background, scholars from different disciplines or schools might interpret the same model description in a totally different way and come to different conclusions.

   Such guessing might lead to metaphorical and theoretical plasticity (Hare and Deadman, 2004) if the same implementation of a model can be explained and justified by the use of more than one metaphor or theory. In the ODD protocol, the basic principles ask for general concepts, theories, hypotheses, or modelling approaches that are underlying the design of a model. The guiding questions do not include the assumptions that underlie the decision-making in particular and the reasons for choosing a certain concept or theory. Apart from a theoretical basis, the choice of decision model may be based on empirical observations \data. This is crucial information for the reader of a model description and should be mentioned explicitly. This was not accounted for in the ODD section on basic principles.

3. In part, the structure of the design concepts in the ODD protocol does not follow a logical order when it is used to describe human decision-making. For example, the ODD protocol foresees that prediction shall be explained before sensing, although agents usually sense their environment before they predict possible outcomes of their decision-making.

Finally, some minor aspects of the ODD protocol might be elaborated that could also be relevant for models that do not include human decision-making: (a) Stating the target group of a model makes its influence on model design transparent, but is not asked for in the ODD protocol. (b) In the ODD protocol, internal and environmental state variables are not clearly defined; thus, Polhill et al. (2008) suggested using the terms “endogenous” and “exogenous” instead. (c) Space is included in the ODD protocol, but its importance could be highlighted. (d) Heterogeneity, a very important issue for ABMs, was not discussed in a separate design concept. (e) The published attempts to replicate ABMs have shown that model results often cannot be reproduced or are based on assumptions that differ from the ones stated in the publication. Therefore, implementation details that are lacking in the ODD protocol, including where to find possibly available source code, need to be added.

6.1.2. The ODD+D Protocol: Adapting ODD for describing decisions in ABMs

Definitions of terms

The consideration of human decisions is a crucial aspect of agent-based complex models and an important issue in various disciplines. However, the definitions of terms vary widely. In this section, we specify our definitions of the most ambiguous terms. Because we are considering ABMs, our first task is to clarify our definition of the term “agent”: Following the definition given in Tesfatsion (2006), we define an agent as ”bundled data and behavioral methods representing an entity constituting part of a computationally constructed world”. This allows for the consideration of human beings, social groupings and institutions or biological and physical entities as agents Tesfatsion (2006). The ODD+D extension is designed for human decision-making. However, it may also be applied to non-human agents to describe their simulated actions in a detailed way without any limitations.
With “decision-making”, we refer to“the methods agents use to make decisions about their behavior” (Dibble, 2006). Two important concepts are often confused: adaptation and learning. For “adaptation”, we adopt the definition given by Dibble (2006): Adaptation “is generally distinguished from learning by being passive and biological rather than active and cognitive”. We operationalize this distinction in the following way: “Agents” decision rules are prone to adaptation, where the information used by the rules to generate a decision changes, and learning, where the rules themselves change over time.

Any confusion that resulted from the application of the original ODD protocol concerning the definition of the terms “entities” and “state variables” has already been addressed in the updated ODD protocol (Grimm et al., 2010). Here, we will follow the proposed definitions: “An entity is a distinct or separate object or actor that behaves as a unit and may interact with other entities or be affected by exogenous factors (drivers). Its current state is characterized by its state variables [...]. A state variable [...] is a variable that distinguishes an entity from other entities [...], or traces how the entity changes over time”. Therefore, the above-defined agent is one specific type of entity. Furthermore, Polhill et al. (2008) criticize the lack of delineation between state variables and parameters. According to our understanding, state variables are the minimal set of variables that completely describe the system and are dynamic. Parameters are static but can vary between simulations, scenarios or agents.

A further lack of clarity refers to the understanding of internal and environmental state variables in the ODD protocol. Environmental variables could also be internal, e.g. rain depending on the evapotranspiration calculated within the model. Therefore, we follow the proposition of Polhill et al. (2008), and use the terms endogenous and exogenous instead. Variables that can be influenced by other variables of the model should be referred to as endogenous, whereas those that cannot be influenced by other variables should be referred to as exogenous. From our point of view, the usefulness of the ODD protocol for ABMs can be enlarged if these exogenous factors, also called drivers, are explicitly listed separately, which has not been the case up to now. In land-use science, a driver is defined as an exogenous variable that influences actors and/or changes in land use but is not influenced by them (see also Turner et al., 1995).

Structural changes between the ODD protocol and the ODD+D protocol

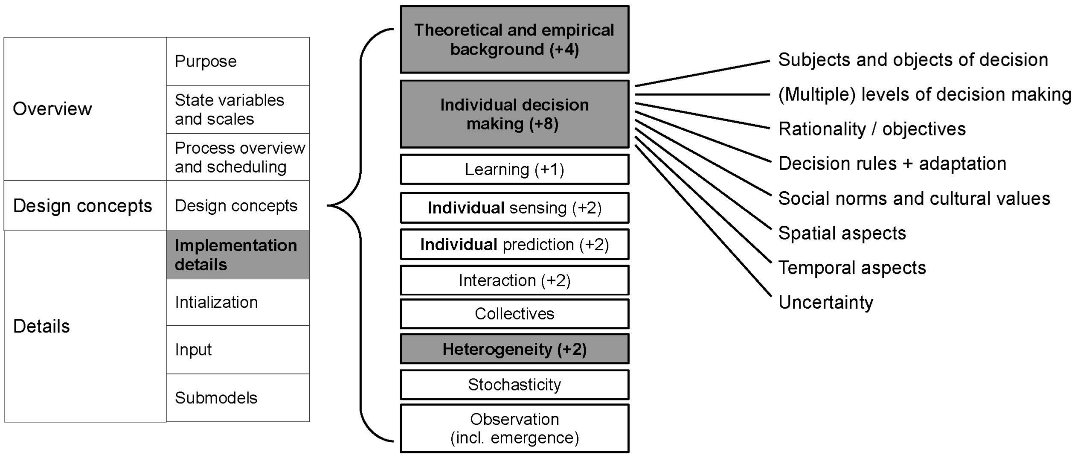

Figure 6.1.: The structure of the ODD+D protocol. Grey boxes indicate new design concepts/categories compared to the ODD protocol. The numbers of new questions added are noted in parentheses. The different aspects of the new design concept "Individual decision-making" are displayed on the right.

The main idea behind the ODD+D protocol is to preserve the basic structure of the ODD protocol to foster the establishment of the ODD protocol as a standard. Hence, changes were mainly made to the Design concepts block (see Figure 6.1). It is more difficult to standardize this block across different disciplines and Grimm et al. (2010) already anticipated that the list of design concepts may need to be enlarged. Note:

“The block … “Design concepts” does not describe the model itself, but rather describes the general concepts underlying the design of the model” (Grimm et al., 2006).

The ODD protocol was structurally changed as follows for the ODD+D protocol: The design concept

“Basic Principles” was renamed “Theoretical and Empirical Background” and expanded to emphasize the importance of information regarding the sources of the assumptions and data used in a model. The ODD design concept “Objectives” was merged into the new design concept “Individual decision-making”, which summarizes the conceptual background of the decision model (see the right side of Figure 6.1). We deleted “Adaptation” as separate design concept because we see adaptation as part of “Individual decision-making” (see Section 3.1, Definition of terms).
“Sensing” and “Prediction” were expanded, and their order was reversed to reflect the characteristics and timeline of human decision-making. For the same reason, “Interaction” was expanded.
A new design concept, “Heterogeneity”, was introduced as it is a property that often distinguishes ABMs from other models, and can, therefore, provide crucial insights into their characteristics.
Despite its undisputed importance for ABM modeling, the design concept “Emergence” was moved into “Observation” to reduce the risk that users might mistake it for a feature to be constructed rather than an outcome of the interplay of the model entities. By including “Emergence” in “Observation”, the forms of stochasticity that were put into the model and the patterns that emerge in the models‘ results can be clearly distinguished. Finally, the category “Implementation Details” was included in the “Details” block because we believe that this information will improve comparability and reproducibility (see also Ince et al., 2012).

Usage of the ODD+D protocol

Beyond the requirements formulated in the ODD protocol (Grimm et al., 2006, 2010), we strongly encourage that all questions be answered to avoid an incomplete model description. If the model description is very long, we recommend the following: The complete ODD+D description including the submodels could be published in an Online Appendix using the template provided. Using the template makes the creation of an ODD+D description easier, since some categories can be answered by keywords such as“yes” or “no” instead of full sentences. The use of this tabular form simplifies the comparison of models applied in different studies to a large extent. In the main text, the overview and the design concepts should be copied and, if necessary, shortened. One concern about the ODD protocol is the potential redundancy between the purpose, design concepts and the submodels description. This redundancy can be reduced by not repeating the details already given as design concepts in the submodel description (Grimm et al., 2010). However, this drawback is outweighed by the benefits of a hierarchical model description that first gives an overview and afterwards provides the details with regard to comprehensibility and clarity.

The ODD+D protocol in detail: Guiding questions and examples for describing human decisions in models. We provide both the original questions (Grimm et al., 2010) and the newly proposed questions (in bold print) to present a comprehensive model description

Structural elements		**Guiding questions**
I Overview	I.i Purpose	I.i.a What is the purpose of the study?
		I.i.b For whom is the model designed?
	I.ii Entities,state variables and scales	I.ii.a What kind of entities are in the model?
		I.ii.b By what attributes (i.e. state variables and parameters) are these entities characterized?
		I.ii.c What are the exogenous factors/drivers of the model?
		I.ii.d If applicable, how is space included in the model?
		I.ii.e What are the temporal and spatial resolutions and extents of the model?
	I.iii Process overview and scheduling	I.iii.a What entity does what, and in what order?
II Design concepts	**II.i Theoretical and Empirical Background**	II.i.a Which general concepts, theories or hypothesis are underlying the models‘design at the system level**(s)** of the submodel**s (apart from the decision model)?** What is the link to complexity and purpose of the model?
		II.i.b On what assumptions is/are the agents‘decision model(s) based?
		II.i.c Why is/are certain decision model(s) chosen?
		II.i.d If the model/submodel (e.g. the decision model) is based on empirical data, where do the data come from?
		II.i.e At which level of aggregation were the data available?
	II.ii Individual Decision-Making	II.ii.a What are the subjects and objects of the decision-making? On which level of aggregation is the decision-making modeled? Are multiple levels of decision-making included?
		II.ii.b What is the basic rationality behind agent decision-making in the model? Do agents pursue and explicit objective or have other success criteria?
		II.ii.c How do agents make their decisions?

II Design Concepts	**II.ii Individual Decision-Making**	**II.ii.d Do agents adapt their behavior to changing endogenous and exogenous state variables? And if yes, how?**
		II.ii.e Do social norms or cultural values play a role in the decision-making process?
		II.ii.f Do spatial aspects play a role in the decision process?
		II.ii.g Do temporal aspects play a role in the decision process?
		II.ii.h To which extent and how is uncertainty included in the agents'decision rules?
	II.iii Learning	II.iii.a Is individual learning included in the decision process? How do indicicduals change their decision rules over time as a consequence of their experience?
		II.iii.b Is collective learning implemented in the model?
	II.iv **Individual** Sensing	II.iv.a What **endogenous** and **exogenous** state variables are individuals assumed to sense and consider in their decisions? **Is the sensing process erroneous?**
		II.iv.b What state variables of which other individuals can an individual perceive? **Is the sensing process erroneous?**
		II.iv.c What is the spatial scale of sensing?
		II.iv.d Are the mechanisms by which agents obtain information modeled explicitly, or are individuals simply assumed to know these variables?
		II.iv.e Are the costs for cognition and the costs for gathering information explicitly included in the model?
	II.v **Individual** Prediction	**II.v.a Which data do the agents use to predict future conditions?**
		II.v.b What internal models are agents assumed to use to estimate future conditions or consequences of their decisions?
		II.v.c Might agents be erroneous in the prediction process, and how is it implemented?
	II.vi.Interaction	II.vi.a Are interactions among agents and entities assumed as direct or indirect?
		II.vi.b On what do the interactions depend?
		II.vi.c If the interactions involve communication, how are such communications represented?

II Design Concepts	II.vi.Interaction	**II.vi.d If a coordination network exists, how does it affect the agent behavior? Is the structure of the network imposed or emergent?**
II Design Concepts	II.vii Collectives	II.vii.a Do the individuals form or belong to aggregations that affect and are affected by the individuals? Are these aggregations imposed by the modeler or do they emerge during the simulation?
II Design Concepts	II.vii Collectives	II.vii.b How are collectives represented?
II Design Concepts	**II.viii Heterogeneity**	**II.viii.a Are the agents heterogeneous? If yes, which state variables and/or processes differ between the agents?**
II Design Concepts	**II.viii Heterogeneity**	**II.viii.b Are the agents heterogeneous in their decision-making? If yes, which decision models or decision objects differ between the agents?**
II Design Concepts	II.ix Stochasticity	II.ix.a What processes (including initialization) are modeled by assuming they are random or partly random?
II Design Concepts	II.x Observation	II.x.a What data are collected from the ABM for testing, understanding and analyzing it, and how and when are they collected?
II Design Concepts	II.x Observation	II.x.b What key results, outputs or characteristics of the model are emerging from the individuals? (Emergence)
III Details	**III.i Implem. Details**	**III.i.a How has the model been implemented?**
III Details	**III.i Implem. Details**	**III.i.b Is the model accessible, and if so where?**
III Details	III.ii Initialization	III.ii.a What is the initial state of the model world i.e. at time t=0 of a simulation run?
III Details	III.ii Initialization	III.ii.b Is the initialization always the same, or is it allowed to vary among simulations?
III Details	III.ii Initialization	III.ii.c Are initial values chosen arbitrarily or based on data?
III Details	III.iii Input Data	III.iii.a Does the model use input from external sources such as data files or other models to represent processes that change over time?
III Details	III.iv. Submodels	III.iv.a What, in detail, are the submodels that represent the processes listed in "Process overview and scheduling"?
III Details	III.iv. Submodels	III.iv.b What are the model parameters, their dimensions and reference values?
III Details	III.iv. Submodels	III.iv.c How were the submodels designed or chosen, and how were they parameterized and then tested?

Table 1 provides a complete list of the guiding questions for each element of the extended ODD+D protocol. A template for using the ODD+D protocol, including examples for possible answers to the guiding questions, is available on the website http://www.ufz.de/index.php?de=10464.
The questions that have been added are displayed in bold. In the following paragraphs, the questions are explained more in detail and examples and literature references are given. In the examples and literature references, emphasis is put on the new part for describing the decision model. In this part, the guiding questions are mentioned again to facilitate orientation.

I Overview

The overview section consists of the subsections i) purpose, ii) state variables and scales, and iii) process overview and scheduling. In the following, we summarize the original description of the ODD protocol (see Grimm et al., 2010)) and our extensions. The citations from the original ODD protocol are given in double quotes.

I.i Purpose

Grimm et al. (2010) state "... ODD starts with a concise summary of the overall objective(s) for which the model was developed. Do not describe anything about how the model works here ... ". We suggest adding to this subsection some meta information that will facilitate understanding of the study, particularly whether the study was mainly designed for hypothesis testing, theory development, quantitative predictions, management and decision support, or communication and learning (e.g. Simon and Etienne, 2010). For whom is the model developed: scientists, students/teachers, stakeholders, or decision-makers?

I.ii Entities, state variables and scales

The intention of this section is well summarized by the guiding questions: "What kinds of entities are in the model? By what attributes (i.e. state variables and parameters) are these entities characterized? What are the temporal and spatial resolutions and extents of the model?" In social-ecological models, the entities will mainly be agents (e.g. humans, households, institutions), spatial units (e.g. grid cells), environments and collectives (list of agents). The different types of agents should only be mentioned here, as the detailed description will follow in the context of the Design Concept "Heterogeneity".
In addition to the mentioned state variables in Grimm et al. (2010), state variables such as land ownership and memory are frequently used in social-ecological ABMs. In addition to the original ODD protocol, we suggest the inclusion of the question "If applicable, how is space included in the model?" at this point in the protocol. To avoid wrong expectations, the authors should explicitly mention if they do not consider space at all. We think it is of special interest whether space is represented in models implicitly or explicitly, and if explicitly, to specify by which spatial dynamics

the landscape is linked and whether the modeled space is based on real landscapes (e.g. based on GIS data).
Additionally, all exogenous factors/drivers should be listed in this section because this will inform the reader from the outset whether the factors/drivers (e.g. precipitation or prices) are influenced by processes or other state variables during a model run or whether they are assumed to be exogenous.

I.iii Process overview and scheduling

Invaluable information for reimplementing the described model is given in this subsection. Such a description may be substantially facilitated by a graphical representation or a pseudo-code representation of the scheduling (Richiardi et al., 2006). Self-explanatory names for the models' processes foster a clear and concise description of the process overview. The authors should also inform the reader as to how the update process is implemented in the model (e.g. synchronous vs. asynchronous updates). In the following section, we introduce ten design concepts that are partly based on the previous ODD protocol (Grimm et al., 2010), extended and ordered from general to detailed information. There is a gradient from the overall view (the theoretical and empirical background, individual decision-making and learning) to the details (e.g. individual sensing and prediction). The stochasticity and observation relate to more technical questions and were therefore placed at the end of the section. Details of the implementation, such as the underlying equations, should, however, not be mentioned here but should appear in the submodels section. We provide guiding questions that should be answered by the model description and examples that help writers to give precise answers. This will give readers of the description a more profound understanding of the simulated decision-making process.

II Design concepts

II.i Theoretical and empirical background

II.i.a The aim of this section is to describe the general concepts, theories or hypotheses that underlie the models' design. The answer should provide more precise information on the underlying theories; for example, the population dynamics theory and resilience thinking in Schlüter and Pahl-Wostl (2007), see the example description below. In contrast to Grimm et al. (2006), we do not ask for the modeling approach because the focus of the ODD+D protocol is only ABM.

II.i.b To compare the different models regarding the assumptions on which their representation of decision-making is based, it is important to note whether specific behavioral theories (such as profit maximization, bounded rationality, cognitive models, social psychology approaches and mental models) real-world observations (mechanistic or process-based explanation, statistical regression methods and heuristics), ad-hoc rules (dummy rules and assumptions) or their combinations were used (see Johnson and Busemeyer, 2010, for a recent review of the theoretical approaches for modeling decision-making under risk and uncertainty).

II.i.c There may be many reasons behind the motivation for choosing a certain decision model, e.g. data (non)availability, reference to previous studies, theoretical reasons, or pattern-oriented modeling (Grimm et al., 2005). We believe that the choice of the decision model is often not only based on theory but is (co)determined by such practical factors. While these reasons should be dealt with in more detail in the discussions section of a paper, this question ensures that not only the choice for a certain decision model but also the practical constraints under which it was made can be compared.

II.i.d This section does not ask for the data input into the model in general, but specifically for the empirical data on which the decision submodel within the model is based (e.g. with regards to parameterization, heuristics used, etc.). Such empirical data may stem from participatory approaches (role playing games, e.g. Castella et al., 2005), household surveys, interviews, direct observations, statistical census, archives, field or lab experiments, GIS products (see Smajgl et al., 2011) for an overview of empirical methods to parameterize ABMs.

II.i.e Information on the level of aggregation of the empirical data would be helpful for comparing the model with other models in terms of the data. Data levels might, for example, be at the individual, household or group level or there may be different resolutions of input data.

II.ii Individual decision-making

The following questions represent an important part of the extension of the ODD protocol with regards to the representation of decision-making in a model, as they explicitly address the basic design concepts behind it.

II.ii.a The documentation of the decision-making processes included in a model requires, first of all, that the subjects and objects of these processes are made explicit. The subjects are necessarily agents according to the definition above (see Section 3.1) and might belong to several different types, whereas the objects might be other elements of the model or may also be agents. As an example, farm household agents (subjects) might decide about the land-use state of land parcels they own (objects). The questions regarding multiple levels address models in which the decisions made on one level affect decisions made on higher or lower levels of aggregation; for example, farmer and government agents (Schlüter and Pahl-Wostl, 2007).

II.ii.b In this section, we focus the more general "Objectives" block from the ODD model on the specific characteristics of human decision-making. The rationality behind decision-making is crucial for understanding the role of decision-making in a model. It includes, for example, whether agents optimize according to an explicit objective, whether they have other types of success criteria, such as meeting aspiration thresholds, or whether they have no explicit objectives at all, as might be the case when decision-making heuristics are used. If agents have some type of success criterion, it should also be mentioned, whether they pursue it in a perfectly rational manner or whether their rationality is in some respects bounded, for example by limited information, limited cognitive capabilities, or limited decision-making time.

II.ii.c The question on how agents make their decisions refers to the way in which the rationality behind decision-making is translated into specific decision-making rules. For example, the pursuit of an objective might be implemented through the optimization of an objective function via mathematical programming, whereas decision-making heuristics might be represented in a decision tree (Schreinemachers and Berger, 2006).

II.ii.d In this section, information shall be given on how agents adapt their behavior to changing state variables, both endogenous and exogenous. Examples of agents adapting their behavior is the adaptation of the number of irrigated fields to budget constraints and water inflow (Schlüter and Pahl Wostl 2007, see the example in Section 3) and of the mobility pattern of pastoralists to multiple stressors such as climate and policies (Boone et al., 2011). Because there is no universal agreement in the relevant literature on how to distinguish adaptation from learning, we have decided to use the one provided above in the "Definitions of terms" section (Section 3.1). According to this definition, adaptation occurs within given decision rules, whereas learning changes those rules.

II.ii.e Because real-world decision-making often takes place in relation to an individuals' social environment, it can be argued that social norms or cultural values should be reflected in models of decision-making (Van den Bergh et al., 2000). For example, trust between agents can be a basis for cooperation (Janssen and Ostrom, 2006b), or traditional perspectives can represent an alternative strategy to purely economic profit maximization (Millington et al., 2008).

II.ii.f Space plays a role in an agents decision-making process if the decision is influenced by the absolute or relative position of the agent or another entity in the model space. McAllister et al. (2006) investigated the role of spatial (and temporal) variations on the efficiency of the agistment networks in Australia using an ABM. Further examples can be found in An (2012).

II.ii.g Temporal aspects enter the decision process if agents' decision-making takes into account past experiences or expectations for the future. Past experiences might be incorporated in some representation of the agents‘ memory, which might also be related to agent learning (see Section II.iii below). The formation of expectations about the future depends on the ability of the agents to make predictions (see Section II.v below).

II.ii.h The information that the agents obtain may be characterized by uncertainty because, for example, agents have limited knowledge about future developments in the model. Thus, this section asks for a summary of the reactions to this uncertainty used in the model, which might enter the agents' decision-making process at different points. Uncertainty might, for example, be included in different learning processes (see Section II.iii below), such as Bayesian learning, which seeks to gradually reduce uncertainty, or it might be directly manifested in the decision-making process, e.g. in the form of a satisficing rule Gotts et al. (2003) or in the form of risk aversion Quaas et al. (2007).

II.iii Learning

II.iii.a Learning is defined on the level of the individual by changes in each ones' decision-making rules. This is the part of the model documentation where different types of established learning representations can be cited (Brenner, 2006) or where the general idea behind the learning model can be described, e.g. reinforcement learning or belief-based learning.

II.iii.b Learning does not only take place on an individual level but also takes place on a collective level, when agents are able to exchange information. For example, different types of evolutionary algorithms can be used to represent how land-owner agents collectively “learn to interact, cooperate, and compromise” to decide about the use of common resources (Bennett and Tang, 2009) or how researchers collectively learn to improve their publication practices (Watts and Gilbert, 2011).

II.iv Individual sensing

Compared to ecological sensing, where organisms or populations perceive their local environment, sensing becomes more complex in the context of human decision-making. Using societal structures, information may be transported on the global level. The following questions help to reflect on what information is exactly available before an agent has to decide. Thereby, all sensing processes may be erroneous.

II.iv.a In this section, the endogenous and exogenous state variables that agents are assumed to sense and consider in their decisions are summarized. Land managers may perceive the availability of (multiple) resources which include working power, monetary resources and different sources of income (e.g. Smajgl and Bohensky, 2013). Further, they may perceive the behavior and actions of other agents (as opposed to the characteristics of other agents, see the following question) or market conditions. Additionally, the observation of the state of the natural resources can be erroneous (cf. Milner-Gulland, 2011, for a modeling study applying the management strategy evaluation approach).

II.iv.b This question refers to direct or indirect contact between agents that enables them to exchange information on their individual state. Signals may be sent between agents intentionally (e.g. Matthews, 2006) or unintentionally. Furthermore, it is asked whether the sensing process is erroneous.

II.iv.c The spatial scale of information flow may be local, global or via a network in the model space.

II.iv.d Sensing may be implemented via mechanisms by which agents obtain information explicitly, or via the assumption that agents simply know these variables. In the former case, signals or messages may be sent between agents (e.g. Matthews, 2006), which takes a certain amount of time within the model space so that information may not be available at once in every time step and may not be available to every agent.

II.iv.e This section asks whether the costs for cognition and costs for gathering information are included in the model. If the resources for gathering information are limited, it may be useful to include costs for different types of information acquisition, as e.g. motivated by the critique of rational choice (Simon, 1957).

II.v Individual prediction

The first question asks for data used by the agents for prediction, the second for their internal model and the last for their prediction error. The information used by the agent can be based on actual (spatial) observation, on experience or on a mixture of both. The agents‘ internal model describes how the agent processes the collected data to get predictions. This could be influenced by mental models such as a pessimistic versus optimistic view of the agents (e.g. Lux and Marchesi, 1999). The prediction error can, for instance, result from limited information processing capabilities of the agents or from unknown consequences of interactions with other resource users (e.g. unknown water extraction of upstream agents in Schlüter and Pahl-Wostl, 2007).

II.vi Interaction

We explicitly add the interactions between agents and entities in addition to the interactions among agents. Both can be mediated by the environment (Schlüter and Pahl-Wostl, 2007), by markets (Deadman et al., 2004) or auctions (Schreinemachers and Berger, 2011). The interaction itself depends on conditions (e.g. spatial distance, access to a resource). Additionally, we introduce a question about whether a (de)centralised or group-based coordination structure of the agents exists.

II.vii Collectives

Agents can belong to aggregations such as social groups, human networks or other organizations. These collectives can either emerge during the simulation or be defined by the modeler.

II.viii Heterogeneity

Agent heterogeneity is one of the characteristic features of ABMs. Agents may differ in parameters (e.g. managerial abilities, Happe et al. (2006); or preferences, Filatova et al. (2011)). They can also be heterogeneous in their decision-making in terms of the different decision models (e.g. Jager et al., 2000, Acosta-Michlik and Espaldon, 2008) and in Murray-Rust et al. (2011) or in their decision objects. If agents only differ in their state variables e.g. the location in space or financial budget, but are the same otherwise, we do not consider this population to be heterogeneous because exchanging an agent at the beginning of the simulation would not change the outputs of the simulation.

II.ix Stochasticity

To understand the model, it is crucial to know which processes include randomization. Examples for coincidence in models can be the random initialization of the values of agents' state variables (e.g. Balmann, 1997, Matthews, 2006), location of households on a map (e.g. Castella et al., 2005) or market-prices that influence agent decisions (e.g. Janssen et al., 2000).

II.x Observation

The questions asked in this paragraph aim to clarify which model output is collected at what time point in the simulation. It should also be stated which of the model results are a result of emergence.

III Details

The technical information that is needed to replicate the model and the experiments should be provided in this block (Grimm et al., 2006). This includes information on model implementation, availability of the models source code, model input data and a detailed (mathematical) description of the submodels.

III.i Implementation Details

Information on the model implementation should be delivered in this section. This includes stating the programming language or modeling platform in which the model was implemented. For a list of further important implementation details, we refer to the "Guide for Authors" of the journal Environmental Modeling and Software and \or the data availability section (cf. EMS, 2012). Authors are encouraged to make the model code accessible (Janssen, 2009, Ince et al., 2012). If the model code was published, for example, in an open model library such as openabm.org, please state where it can be downloaded.

III.ii Initialization

III.iii Input data

III.iv Submodels

We adopted the initialization, input data and submodels elements almost as-given by Grimm et al. (2010). However, in the element "Initialization", we added the case that the data could be based on stakeholder choice.

6.2. Sample application of ODD+D

We present a sample application of the ODD+D protocol for describing an ABM of water use (Schlüter and Pahl-Wostl, 2007). The model has been used to compare the performance and resilience of a centralized and decentralized water governance system with single or multi-purpose water use in the face of uncertain water flows. The centralized version is a stylized representation of water management in the Amudarya river basin in Central Asia.

I Overview

I.i Purpose

The purpose of the model is to understand how different governance structures (centralized versus decentralized) and diversity of water use affect the resilience of a farming community to variable and uncertain water flows. The model has been designed for scientists, particularly those interested in natural resource governance and resilience, with the aim of testing hypotheses about resilience mechanisms.

I.ii Entities, state variables and scales

The model consists of two types of human agents, individual farmers and a regulator such as a national government authority, and one animal agent, an age-structured fish population. A fourth entity is the water resource. Water is modeled as the units of water that enter the river stretch upstream and are then distributed downstream along the river onto the fields and into a terminal fishing lake. Farmers are characterized by their location along the river and hence the distance to the water inflow and the fishing lake, the number of fields they irrigate, their individual expectation of the water available each season, their memory of past water deliveries, the yield they receive from cultivating their fields, the catch from fishing, and the financial budget that is determined by their net returns from agriculture and fishing activities. The national authority is characterized by the total number of fields irrigated in the area, its expectation of water availability each season, its memory of past water flows and a budget that is the sum of all of the farmers' net incomes from irrigation.

The fish population is composed of 12 age classes. Age 0 is larvae that are born in the lake or migrate to the lake from upstream, ages 1-4 are juveniles and ages 5-12 are adult. Each age group is characterized by specific density-dependent and density-independent mortalities, birth and reproductive rates and, in the case of the age 0 class, a migration rate.

The water entity is characterized by a unidirectional flow that is reduced by irrigation uptakes by the farmers. The remaining water at the downstream end of the river stretch enters the lake where the fish population is located. Water inflow into the river stretch from upstream is an exogenous variable. The parameters of the model are given in Table 2 of Online Appendix B.

The governance structure is represented by two different model structures, a centralized and a decentralized version, that differ in terms of which type of agent (farmer or national authority) makes the decisions on the number of fields to irrigate in a season and hence the amount of water to withdraw from the river.

Space is implicitly included through the location of each farm along the river stretch, which determines the farms' access to water and to the fish resources as well as the information each farmer has on the water flows. There are nine farms along the river. The model runs with monthly time steps over a period of 200 years. Decisions about the number of fields to irrigate in a season are taken at the beginning of a season.

I.iii Process overview and scheduling

Within each year, a sequence of activities takes place in the following order. In the centralized version at the beginning of the season (April), the national authority predicts the expected water inflow to the river stretch and decides on the number of fields to irrigate. The farmers calculate their water demand and irrigate the fields each month with the water actually available. Crops experience water stress when they do not receive the required amount of water. The remaining water after all fields have been irrigated, if any, flows into the lake. At the end of the year, the fish population grows, the farmers fish and harvest, and the national authority calculates its budget.
In the decentralized version, all farmers make their individual prediction of the expected water availability at their location along the river stretch at the beginning of the season, and decide on the number of fields to irrigate. They calculate the water needed to irrigate their fields each month. They irrigate the fields each month with the actually available water. Crops experience water stress when they do not receive the required amount of water. The water remaining after all fields have been irrigated, if any, flows into the lake. At the end of the year, the fish population grows and the farmers fish, harvest and calculate their individual budgets. Each agent is updated in the sequence determined by its location along the river stretch.

II Design concepts

II.i Theoretical and empirical background

The hypothesis that this model was designed to test was informed by resilience thinking (Folke et al., 2010). The modeling of the fish population growth is based on population dynamics theory, in particular, the Ricker model (Ricker, 1954). The water distribution and the impact of water stress on crop yield are modeled based on standard hydrological and agricultural approaches. The agents' decision model is based on the assumption that their information processing capacity is limited and that they have only partial information on water availability, hence they are boundedly rational (Simon, 1957). The agents use a form of inductive reasoning (Deadman et al., 2000) and rely on heuristics that guide their behavior (Ostrom, 1994). They have no foresight. They are satisficers who, once they are above a certain minimum income threshold, engage in a process of trial and error to determine their best irrigation strategy based on their experience with past strategies. It is also assumed that the agents have different memory strengths with respect to past water flows. The memorystrength affects their prediction of future water availability. The decision model of the national authority is based on real-world heuristics of water allocation. It is a simplified caricature of decision-making in the case study.
The ad-hoc decision model for the decentralized version was chosen because a decentralized setting does not exist in the case study and hence there are no data. The calculation of the expected water availability is based on the assumption that agents

have different memories of past events and value this past experience differently. The method is based on a discounting approach used before in models of agent past memory (Satake et al., 2007). A 15-year runoff time series for a gauging station at the entrance to the Amudarya river has been used to determine the exogenous inflow to the river stretch (Schlüter et al., 2005).

II.ii Individual decision-making

Decision-making is modeled on two different levels, the national and the local. In the centralized version, the national authority decides the number of fields to be irrigated by the farmers along the entire river stretch. Farmers only execute the decisions. In the decentralized version, each individual farmer decides on the number of fields to irrigate on the farm. The number of fields determines the amount of water diverted to the farm (if available).

The agents pursue the objective of finding the number of fields they can irrigate with the uncertain water supply and a limited budget. They try to find the best strategy by adapting the number of fields based on an evaluation of their past performance. They do so by adapting their behaviour to changes in expected water availability, experienced water flows, yields and budget. The heuristics the agents use to make a decision on how many fields to irrigate are represented in a decision tree.

Social norms or cultural values and spatial aspects do not play a role in decision-making; however, the latter influence the outcome of the decision. The decision on how many fields to irrigate is influenced by the memory of past water availability. Agents can have different memory strengths, i.e. they weigh the experience from past years more or less strongly. Note, however, that within a simulation run, the agents do not differ in their memory strength.

Uncertainty is not explicitly included in the agents' decision rule; however, agents try to address the uncertainty of water flows by taking past flows as a predictor of future ones. The willingness of individual farmers to change their irrigation strategy and hence take the risk of losing their investment depends on their past income level. If the level is below a minimum value, the farmers take more risks.

II.iii Learning

No individual or collective learning is included in the decision process.

II.iv Individual sensing

The national authority knows about the realized water flows into the river stretch (note that this happens after the decision on the number of fields to prepare for irrigation has been made), the total agricultural budget available and the total irrigation costs. The farmers know in hindsight the amount of water delivered to their fields, their own budget, the costs of irrigation and the crop yields. Hence for the national authority, the spatial scale of sensing is global; for the farmers, the spatial scale is local. The agents receive this information for the on-going year without error. Farmers do not know any of the state variables for other farmers, but the national authority knows the net returns from irrigation of each farmer in the centralized version. In the model implementation, agents are assumed to simply know the values of the relevant variables, i.e. they do not carry out any activities to receive this information. The costs for cognition or for gathering information are also not explicitly included.

II.v Individual prediction

The national authority uses the information on past inflow to the river stretch to predict future water flows; the farmers use the information about past water deliveries to their fields to assess how much water they can expect in the next year. The agents make their prediction based on their memory of those past water flows. The prediction process is implemented through a weighted average of past water flows, where the weights are determined by the memory strength. The prediction is erroneous because of the variability of water inflows between years that is not known to the agents and the loss of memory of the agents. The downstream agents also do not know the water extraction of the upstream agents.

II.vi Interaction

Interactions among agents are indirect through their water and fish extraction (the resource extracted by one agent is no longer available for the other agents); the interactions are thus a consequence of the resources being common pool resources. The interactions depend on the location of the agent in relation to the water flow and distance from the fishing lake. In the centralized version, the national agency coordinates water use. Here, coordination affects the water extraction decision of each agent. In the decentralized scenario, no coordination mechanism exists.

II.vii Collectives

Agents do not belong to or form any collectives.

II.viii Heterogeneity

There is no heterogeneity of agents. Agents are not heterogeneous in their decision-making.

II.ix Stochasticity

Within the catchable age classes of the fish population, the actual age class from which a fish is caught is modelled randomly.

II.x Observation

The annual yields and catch of each farmer, accumulated total returns and abundance of the fish population are collected at the end of each year to compare the two model versions and the different scenarios of memory capacity and diversity of water use and for sensitivity analysis. A distinct pattern of distribution of yields along the upstream-downstream gradient emerges.

III Details

The model was implemented in Java using the Repast platform. The source code can be made available upon request. The model world is initialized with nine farmers that all have the same initial budget, number of irrigated fields, yields and memory capacity but differ in their location along the river. The national authority in the centralized scenario has an initial budget, an initial number of fields and a memory capacity. The initial values for the agents and the fish population have been determined through calibration. The initial number of fields is varied among simulations to reflect scenarios with a strong focus on agriculture or fisheries. The inflow to the river stretch is provided by a data file of the observed characteristic runoff time series for the Amudarya River. The model has a main part that models the actions of the two types of agents (the farmers and the national agency) and two submodels that represent the two resources (water and fish). The model parameters, their dimensions and default values are given in Table B.2 of Online Appendix B.
The remaining details section is described in Online-Appendix B. There, the completed template for the ODD+D protocol for this example can also be found.

6.3. Discussion

The documentations of ABMs that include human decision-making often do not describe the details that are needed to understand and replicate the decision-making part, particularly with respect to the underlying assumptions and theories on which the agents' decision making is based. Using standardized protocols can help to provide model descriptions that meet this need. The ODD protocol is now widely used for describing agent- or individual-based models in general, but lacks the details relating to decision-making. Therefore, we have introduced an extension for the ODD protocol to describe human decision-making in ABMs: ODD+D.

6.3.1. Expected benefits from ODD+D

Using standardized protocols to describe simulation models offers many advantages (see also Grimm et al., 2010): The experienced scientific audience can understand the models described with a standardized protocol more easily, and meta-analyses on existing models is facilitated. Our protocol also eases the use of the taxonomy of ABMs suggested by Hare and Deadman (2004): The three taxonomy levels (coupling social and environmental model, social interaction and intrinsic adaptation) are covered in Sections I.ii, II.vi and II.ii.d of the ODD+D protocol, respectively. Referees of scientific articles may find it easier to review a manuscript that draws upon such a protocol. Modelers do not have to decide upon the structure of their model description, as the structure is already given by the protocol. And finally, modelers-to-be seeking guidance on and thinking about what aspects of a model have to be conceptualized before implementing the model, might use the ODD+D protocol as a checklist for the model development process.

6.3.2. The added value of the ODD+D protocol compared to the ODD protocol

The ODD+D protocol enhances the original ODD protocol in three ways: First, it incorporates the central aspects of human decision-making into the design concepts section resulting in a considerable re-organization of this section. New components on individual decision-making and heterogeneity were added, and numerous questions regarding concepts that are missing in the ODD protocol were included, i.e. coordination, temporal aspects in decision-making, cultural values and the like. Second, greater emphasis has been placed on the theoretical and empirical basis by renaming the "basic principles" section and adding more detailed questions regarding the background of the model in general and the decision-making algorithms in particular. Third, the design concepts were organized (including a reversed order) in a hierarchical fashion. Finally, minor aspects have been revised, such as adding questions regarding target groups, exogenous factors, space and implementation details. By implementing these alterations, the ODD+D protocol allows for a concise and well-structured documentation of human decision-making in a more straightforward way than the original ODD protocol. In the example description, the ODD+D protocol helped to make the theoretical foundations of the decision-making algorithms more explicit, which would not have been possible with the ODD protocol. This makes it easier to link the model results to the results of other models that are based on similar assumptions about the decision-making process. It also facilitates the assessment of model results in view of the underlying assumptions and thus promotes a better understanding of the robustness and scope of the results. The ODD+D protocol also provides for the specification of the empirical data used as input to the model, which would not have been mentioned in the ODD protocol. This allows for a better understanding of how the model relates to a real-world setting. Finally, the questions about individual decision-making specify the details of the decision making process that would not be revealed in the ODD protocol but are relevant for assessing model outcomes, e.g. how the memory of past water flows affects the performance of individual farmers and the overall system in the face of inflow uncertainty.

6.3.3. The effort required to use the ODD+D protocol

The ODD+D protocol requires answering a variety of questions, which is inevitably time consuming. Compared to the ODD protocol, the ODD+D protocol, especially the Design concepts section, includes more questions and thus leads to a more lengthy documentation. Therefore, we provide a template that guides the user through the questions. Some of the questions can be answered simply using keywords instead of full-length descriptions. Thus, we think that the additional effort required when using the ODD+D compared to ODD is negligible. The wide usage of the ODD protocol shows that a detailed protocol is currently well received by the scientific community. We believe that the ODD+D protocol will make the documentation of human decision-making easier.

For users who have not described their simulation model before, applying the ODD+D protocol definitely requires effort to answer all of the questions. However, the structure provided in the ODD+D protocol will very likely facilitate the whole documentation process, as users do not have to decide upon the structure of their description. Users who already have a model description in the ODD protocol need to consider the additions made by the ODD+D protocol (see 6.1 and Table 1 for a comparison of the ODD and ODD+D protocols). In sum, they need to (1) describe the spatial aspects in the overview section, (2) re-arrange the design concepts section into the ODD+D structure and answer the supplemented guiding questions of the copied design concepts, (3) add (3a) the theoretical and empirical background, (3b) individual decision-making and (3c) heterogeneity in the Design Concepts section and finally (4) provide implementation details in the Details section.

6.3.4. Future work

This first version of the ODD+D protocol was developed based on experiences gained in the social-ecological scientific community. We believe that the ODD+D protocol may prove to be helpful for describing ABMs in general. However, describing models with other thematic foci such as economic, sociological or political research questions might reveal blind spots in the ODD+D protocol. Furthermore, a wider application will show if the current structure of the ODD+D protocol constrains modelers and if model descriptions become very lengthy. Such issues should be addressed in updates of the protocol. This first version is meant as a starting point for a participatory discourse on describing ABMs including human decision-making. The scientific community is invited to try out the ODD+D protocol and participate in discussions on the protocol by contacting the authors of this article. Updates to the ODD+D protocol will be published on the website mentioned in Section 3.4. A further challenge is the development of a ΔODD protocol to describe different model variants (Polhill et al., 2008) and its usage in the ODD+D protocol. This is especially relevant for describing human decisions, as testing the influence of different decision algorithms in a single overall model is often a part of ABM studies. Apart from that, the usability of the ODD+D protocol in the model development part of the TRACE modeling process documentation (Schmolke et al., 2010b) still has to be tested. Finally, the current version of the ODD+D protocol draws solely on written text for describing the model concept and implementation. It might be useful to also provide templates for visualizing individual aspects of the model, for instance using UML or the Web Ontology Language (Polhill and Gotts, 2009). In sum, the ODD+D protocol shall foster the explicit description of the theoretical background of ABMs incorporating human decisions and important details of the model implementation. This enables the scientific community to reproduce simulation results and to further develop already existing models. As the ODD+D protocol also explicitly asks for the underlying theories, the ability of a theory or hypothesis to replicate patterns found in the real world can be assessed more easily. Furthermore, widespread usage of a protocol such as ODD+D would clearly facilitate model comparisons focused on human decisions. The ODD+D protocol might address the "particular need for research that compares these decision making models to extant theory, practice, and observation of the real world" (Parker et al., 2003) by facilitating model comparisons related to specific theories.

7. Standardised and transparent model descriptions for agent-based models - current status and ways ahead

This chapter is based on a joint publication that resulted from a workshop at the iEMSs conference 2012:

B. Müller, S. Balbi, C.M. Buchmann, L. Sousa, G. Dreßler, J. Groeneveld, C.J. Klassert, Q.B. Le, J.D.A. Milington, H. Nolzen, D.C. Parker, J.G. Polhill, M. Schlüter, J. Schulze, N. Schwarz, Z. Sun, P. Taillandier and H.Weise: Standardized and transparent model descriptions for agent-based models - current status and ways ahead. Submitted manuscript.

7.1. Introduction

Agent-based models are argued to be helpful to investigate complex dynamics in coupled human-natural systems (Hare and Deadman, 2004, Liu et al., 2007, Balbi and Giupponi, 2010, Filatova et al., 2013). However, the production of research using agent-based modelling has not been as efficient as it could be up to now. Reasons include that model assessment, replication, and comparison are hampered to a large extent by a lack of transparency in model descriptions. Further, code developed for one project is rarely reused for other projects, even for closely related research. To overcome these problems, standardised model description protocols, ontologies and graphical representations have been created. The various model description types have been developed to achieve different purposes, including facilitation of in-depth model comprehension, assessment, replication, design and communication.

In this contribution we address the question of whether an ideal standard for describing agent-based models exists. We first present a classification of the prevalent types of model descriptions and give an overview of their different purposes. We then review available model description types, evaluating each on its utility for the different purposes. Finally, we discuss advantages of combining these different types, suggest a minimum standard of model description for good modelling practice and discuss future challenges. Note that we set the focus on providing an adequate description of the model itself and not on the description of model results. Appropriate documentation of the model results is beyond the scope of this paper (but see “Transparent and comprehensive ecological modeling (TRACE) documentation” in Schmolke et al. (2010a), pp. 482 which suggests a standard for all parts of the modelling process).

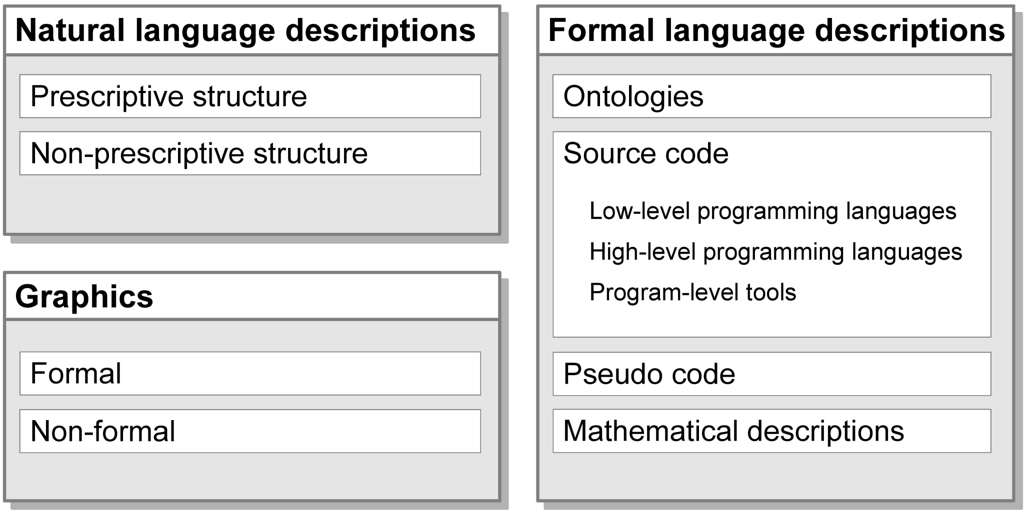

Figure 7.1.: Types of model descriptions

The idea for this article came about at a workshop at the 6th International Congress on Environmental Modelling and Software (iEMSs) 2012 in Leipzig, Germany, and the article reflects the perspectives of the participants, who are members of the integrated social and environmental modelling communities.

7.2. Current state of the art: different types of model descriptions in use

We classify the prevalent types of model descriptions in three categories: natural language descriptions, formal language descriptions and graphics (see figure 7.1 for an overview). In the following paragraphs the different description types are briefly outlined:

Natural language descriptions present models in everyday language with or without a prescriptive structure. The prescriptive approach divides the model description into categories, each explaining a particular part of the model. One example of such an approach is the ODD protocol (Grimm et al., 2010, and its extension to include a description of human decisions in ABMs, ODD+D in chapter 6). ODD describes the model in a hierarchical way using three main categories: Overview, Design concepts and Details that are themselves subdivided into several subcategories such as (in the case of design concepts) sensing or interaction. ODD is being widely used for the description of ABMs (for examples see Balbi et al., 2013, Caillault et al., 2012, Marohn et al., 2013, Smajgl and Bohensky, 2013). In contrast, a non-prescriptive natural language description puts no constraints regarding content and form of the model description on the author (see exemplary model descriptions in Becu et al., 2003, Deadman et al., 2004). Furthermore, non-prescriptive descriptions can also be used to present the source code in a more intuitive way. Examples are literate programming (cf. Knuth, 1984), documentation generators such as Doxygen or Javadoc that assemble source code comments into a structured document, or, in principle, any form of source code documentation that uses natural language.

Formal languages describe models in an abstract and self-consistent way with formal syntax and semantics that avoid ambiguity. Model descriptions written in formal languages may therefore be used to describe important aspects of a model specifically. Formal languages that we consider here include ontologies, source code, pseudo code and mathematical descriptions.

An **ontology** can be defined as "an explicit specification of a conceptualization" (Gruber et al., 1993) that describes entities and their structural interrelationships, often using a hierarchical categorisation. They specifically allow logical inferences to be drawn. Various formal languages are available for writing ontologies - OWL (Web Ontology Language) being currently the most popularly used (Horrocks et al., 2003, Grau et al., 2008). OWL has been argued to improve the transparency of formal descriptions of model structure in comparison with source code, since the latter is focused on programmer and compilation convenience rather than using logics to reflect common-sense perceptions (Polhill and Gotts, 2009). One example of ontologies applied to agent-based modelling is that of Christley et al. (2004). A second example is the MR POTATOHEAD ontology developed by Parker et al. (2008a), which describes the components that appear in agent-based models of land use/cover change. It identifies key model elements and their alternative instantiations, based on a broad review of models. MR POTATOHEAD has an OWL implementation which facilitates evaluating conceptual completeness.

Providing source code is another formal way to communicate models. The following subcategories are listed according to their readability, from cryptic to simple-to-read. **Low-level programming languages** (e.g. assembly language) are characterized by their strong linkage to the computer's hardware and are often platform-dependent. Though unlikely to be used for an entire ABM implementation, these can be useful for computationally intensive functions where bespoke code improves on compiler optimisation. Assembly language is necessary where higher-level programming language libraries are not available for specialised hardware operations. For example, it is common in Linux distributions not to provide C libraries for accessing floating point arithmetic utilities stipulated by the IEEE 754 (1985) standard (IEE, 1985). Polhill and Izquierdo (2005) note that implementation of these utilities using assembly language is necessary in a Cygwin environment.

High-level programming languages in their basic form are platform-independent (especially where governed by standards) and improve the readability for the user by providing algorithmic constructs such as loops or conditional statements. Popular examples of high-level programming languages are Java and C++. In addition, **program-level tools** extend the functionality of high-level programming languages by "providing useful software libraries for building specific classes of models" (de Sousa and da Silva, 2011) and can further improve the readability of the source code. Usually they are tailored to specific fields of modelling. They can be further distinguished into tools that provide a domain-specific language (e.g. NetLogo or GAMA, Tisue and Wilensky, 2004, Taillandier et al., 2012, for agent-based modelling) and tools where the user has to write the application in a high-level programming language (e.g. Repast or Mason North et al., 2007, Luke et al., 2005). In any case, provision of source code has been argued to be a necessary condition of maintaining good scientific practice in the publication of simulation models (Polhill and Edmonds, 2007).

Pseudo code is a structured description of the model combining natural language elements with formal language constructs (e.g. loops). Gilberg and Forouzan (2004) define pseudo code as "[natural language]-like presentation of the steps needed to solve a problem. It is written with a relaxed syntax ... that hides the detail [allowing the reader] to concentrate on the problem requirements." While such definitions can be given, to the knowledge of the authors no common standard on formulating pseudo code exists. Indeed, the provision of such a standard has been argued against on the basis that it would then become another programming language, though there are stylistic conventions (Smed and Hakonen, 2006), especially for operators and control statements. The advantage of pseudo code is that it is independent of the programming language and therefore the knowledge of a specific programing language is not required to read and understand the code (for examples cf. Roy, 2006, Perez and Dragicevic, 2010, Robinson et al., 2013).

Mathematical descriptions provide an exact way to depict model processes and states, usually with formulated equations composed of strings of symbols. While being suited to describe quantitative properties of the model, they are not able to communicate specific model concepts, such as underlying theories or process scheduling. Mathematical descriptions can range from general descriptions of model states (see equation (1) for the calculation of the willingness to pay (WTP)) to specific equations (see equation (2), cf. Filatova et al., 2009).

$$WTP = f(utility, income)$$

$$WTP = \frac{utility \cdot income}{b^2 \cdot utility^2}, \text{ with } b = \text{constant factor}$$

Graphics use particular visualization techniques to illustrate processes, structures, relationships, program flows, etc. They particularly support the understanding of qualitative properties of the model, such as its structure. Graphics can be either formalstrictly adhering to pre-defined rules or protocols, such as UML (Unified Modeling Language, cf. Object Management Group, 2011 and examples for class diagrams, activity diagrams and sequence diagrams in Polhill et al. (2013)), or non-formal-following loosely-defined principles or conventions, such as flow charts (cf. International Organization for Standardization (ISO), 1985, examples in van Oel et al., 2010, Zhang et al., 2011), Bayesian belief networks (Jensen, 2001, Aalders, 2008, Sun and Müller, 2013), decision trees (Quinlan, 1986), cognitive maps (Eden, 1988, Kitchin, 1994) or causal loop diagrams (Maruyama, 1992). Non-formal graphics are often used to get a first impression of the model concept (for examples see Haase et al., 2010, Rebaudo and Dangles, 2013).

It should be noted that the different description types outlined above are not necessarily mutually exclusive. For instance UML, as part of the graphics category, is also an ontology. At the same time, the MR POTATOHEAD ontology can be visualized using various graphical approaches. However from our point of view a separate category "graphics" underpins the importance of visualisation approaches for instance for the communication with stakeholders or scientists from other disciplines.

7.3. Does an ideal standard for describing models exist?

7.3.1. Different purposes of model descriptions

Model descriptions can enable their users to meet various different but related purposes. We propose the following as the most important purposes: model communication, in-depth model comprehension, model-assessment, -development, -replication, -comparison, theory building and code generation (note some overlap occurs between purposes.). Here we briefly describe each of these purposes to facilitate our review of model descriptions and the discussion of an appropriate standard (the order chosen reflects the level of generality, i.e. from general and universal to rather specific purposes):

Communication of the model: Model descriptions serve as a means of communication of the model to an audience that can consist of scientists as well as stakeholders or people from outside the research domain. These groups may need different information (e.g. methodological details for specialists versus basic information on the model's entities and processes for stakeholders). They also need to be approached in different ways, which poses a particular communication challenge. One example is the interaction with stakeholders which may benefit particularly from the use of easily understandable visual tools.

In-depth model comprehension: This is the prime motivation for model descriptions. The challenge is to allow a profound and complete understanding of the model's entities and processes. Ideally, the reader can also relate real-world concepts to the model. Model understanding is the precondition for most of the other purposes. A detailed and thorough description of all model components is thus essential. We emphasise here the degree of detailed model understanding required by other scientists, experts and reviewers (in contrast to the purpose of communication which does not necessarily imply overarching comprehension).

Model assessment: Assessment here means an evaluation of the model with respect to its suitability to answer the research question, the consistency between model design and sub-models, as well as chosen spatial and temporal scales. This purpose is particularly relevant for reviewers, but also researchers or policy makers who want to use model results. To fulfill this purpose the respective information (on research question(s), model purpose, design and scales) must be given together with a clear statement of the underlying model assumptions.

Model development: Model descriptions can also be helpful for model development ('model design'), particularly when the model description is elaborated in parallel to the model design. Ideally, describing the model helps the modeller to adopt another (external) point of view of the model and can act as a check list for completeness. To achieve this, a model description should follow a concise and strict structure which obliges the author to describe all relevant aspects. A structured model description can also facilitate and give guidance to the development of models jointly with stakeholders ('collaborative model development'). In the case where the model description is expected to assist model development up to the final implementation, a rigorous protocol taking into account software and implementation related issues is particularly helpful.

Model replication: Adequate model descriptions can enable model replication. However, different levels of replication (Wilensky and Rand, 2007) may pose different requirements for the model description. Exact quantitative replication of the results (exactly the same numbers) requires much more detailed information than statistical or qualitative replication. One extreme example for such detailed information is the random seed used if the model includes stochasticity. We use the term "qualitative" to refer to replication that produces the same results as the original model (statistically significant) and is robust to implementation details like random number generators or the hardware used. This usage is akin to the concept of "distributional equivalence" in Wilensky and Rand (2007).

Model comparison: Model descriptions can facilitate model comparisons with respect to concepts and techniques (for example fitting or optimization algorithms). This can allow the reader to also evaluate which model(s) are more or less appropriate for investigating certain questions. To achieve this, a strict and complete set of criteria (e.g. aim, scales, and processes) for comparison should be part of the model descriptions, preferably in a standardised structure and format.

Theory building: By communicating the ideas behind a model, a description can also aid in theory building. The challenge and prerequisite here is to embed the respective model (concept) into the existing pool of theories and theoretical concepts. This can be attained most easily when the description standard obliges the author to summarize questions, applied theories, concepts, principles and hypotheses. Such an evaluation of the described model can reveal a lack of theoretical foundation for the model. Thereby, model descriptions can support models in their role of challenging existing theory (cf. Epstein, 2008). This, in turn, together with evaluation of model results, can facilitate the creation and assessment of new theoretical concepts and even new theory.

Code generation: Formal languages and graphic-based model descriptions in particular can support model implementation, specifically through (automated) source code generation. In case of model reimplementation, code regeneration here implies a higher level of formality, compared to most levels of model replication (see above). Code (re)generation can be achieved if a description standard is formal, complete, and exact (not allowing any ambiguities), while containing accurate information on entities and processes plus their translation into code characteristics like classes and methods. In this case, specialised software can then directly generate the basic (code) structure from the model description alone.

7.3.2. Matching purposes and types

In the following, we assess how well the purposes are met by the different description types. For the assessment, we focus on the potential of the description type rather than on how it is realised in practice in our experience. The various description types fulfil the purposes mentioned in the previous section to different degrees (see Table 1 for an overview).

Communication of the model needs to be differentiated for different target groups. (a) Communication for peers is achieved with most of the description types, given the knowledge of the respective description approach/programming language. (b) Communication for education purposes is improved by e.g. natural language descriptions, OWL, usage of program-level tools, pseudo code and mathematical descriptions as well as non-formal graphics. (c) Communication to stakeholders should not be too technical, thus the suitable description types are limited to natural language descriptions, OWL, and non-formal graphics. Non-formal graphics are the only description type that can foster communication for all target groups, due to their large flexibility.

In-depth model comprehension that includes profound understanding of model entities and processes is fostered by natural language descriptions, particularly with prescriptive structure (such as the ODD protocol), but also by formal language descriptions (i.e. OWL ontology, source code in a high-level programming language and of program-level tools) as well as different types of graphics. While being suited to describe quantitative properties of the model, mathematical descriptions alone are not

Table 1: Assessment on how well the purposes are met by the different description types (light grey -limited ability, middle grey - medium ability, dark grey - high ability, x not applicable)

	Natural language		Formal language							Graphics	
	Prescriptive structure	Non-prescr. structure	Ontologies		Source code			Pseudo code	Mathematical descriptions	Formal	Non-formal
	ODD	Verbal descript.	OWL	MR POTATOEHEAD	Low-level progr. lan.	High-level progr. lan.	Program-level tools			UML	Exampl.[2]
Commun. to peers	dark grey	middle grey	middle grey	dark grey	light grey	dark grey	dark grey	middle grey	dark grey	dark grey	dark grey
Commun. for education	middle grey	dark grey	dark grey	middle grey	light grey	middle grey	dark grey	dark grey	dark grey	middle grey	dark grey
Commun. for stakeholders	light grey	dark grey	dark grey	middle grey	light grey	light grey	light grey	middle grey	middle grey	middle grey	dark grey
In-depth comprehen.	dark grey	middle grey	middle grey	dark grey	light grey	dark grey	dark grey	middle grey	middle grey	dark grey	dark grey
Assessment	dark grey	middle grey	dark grey	middle grey	light grey	middle grey	middle grey	middle grey	middle grey	dark grey	dark grey
Developm.: design	dark grey	light grey	dark grey	dark grey	light grey	middle grey	dark grey	dark grey	dark grey	dark grey	dark grey
Developm.: collaborative	middle grey	dark grey	dark grey	middle grey	light grey	light grey	middle grey	middle grey	middle grey	dark grey	dark grey
Replication	middle grey	light grey	light grey	middle grey	middle grey	middle grey	dark grey	light grey	dark grey	middle grey	middle grey
Comparison	dark grey	middle grey	dark grey	dark grey	light grey	middle grey	dark grey	middle grey	dark grey	middle grey	middle grey
Theory building	middle grey	dark grey	middle grey	middle grey	light grey	light grey	light grey	middle grey	middle grey	middle grey	dark grey
Code generation	light grey	light grey	dark grey	light grey	x	x	dark grey	light grey	light grey	dark grey	light grey

[2] Non-formal graphics examples: Cognitive maps, Bayesian belief networks, decision trees, flow charts, causal loop-diagrams

able to communicate specific model concepts, such as underlying theories or process scheduling.

Model assessment in general is facilitated by structured natural language descriptions, ontologies and all types of graphics, i.e. UML, and non-formal graphics such as cognitive maps, decision trees and the like. Some specific types of model assessment - such as checking the consistency between model design and sub-models - can more easily be carried out with ontologies or formal graphics.

Model development: (a) Model design by modellers and programmers is aided with prescriptive natural language descriptions such as ODD, ontologies and usage of program-level tools, pseudo code or mathematical descriptions; both formal and non-formal graphics are also helpful. However, usage of non-formal graphics and also program-level tools as a check list for the model design process is limited, depending on the specific tool chosen. (b) Collaborative development together with stakeholders on the contrary is eased by non-prescriptive natural language descriptions and formal and non-formal graphics. (Quantitatively exact) model replication is possible only with the provision of source code in program-level tools and with mathematical descriptions, although equations alone do not guarantee replications (as discussed in section 3.1). Usually detailed information of the specific analytical or numerical procedures needs to be provided in form of script similar to high-level source code. However, we want to highlight that although the provision of source code technically facilitates model replication, it may circumvent the consistency check between the conceptual model and its implementation (one purpose of model replication) by encouraging "replicators" to simply copy the source code. In addition, for independent model replication it is necessary to know the intention of the modeller and therefore, we suggest that for independent model replications, both source code and a natural language description are provided. Qualitative model replication may be achieved also with other model descriptions, such as MR POTATOHEAD, ODD, UML and non-formal graphics.

Model comparison is made easier with prescriptive natural language descriptions, ontologies, usage of program-level tools and the provision of mathematical descriptions, if parameters are also provided. Again, the specific focus of a model comparison will indicate descriptions that are most suitable from this list (e.g. comparison of the conceptual basis might be easier using prescriptive natural language descriptions or ontologies rather than mathematical descriptions).

Theory building is not well facilitated by model descriptions, as most model description types do not ask for the theoretical background of the model, hypotheses to be tested, etc. One exception is the prescriptive structure of the ODD+D protocol (Müller et al., 2013), which asks for the theories underlying the model; while theories are up to now not explicitly listed in the "basic principles" section of the ODD protocol (Grimm et al., 2010). Another example is presented in Schlüter et al., in press. They develop a procedure to document the theoretical background, the hypotheses and the assumptions on which a model conceptualization is based in a structured way. Furthermore, non-formal graphics are able to convey information relevant for theory building and can thus facilitate theory building without the constraints of formalised graphics.

Code generation in the sense of automatically generating code is enabled by formal graphics, such as UML (cf. Bersini, 2012) or program-level tools facilitating generation of system models such as SIMULINK or STELLA as well as OWL program-level tools. Apart from that, pseudo-code is often used to generate the structure of the program (Roy, 2006).

7.3.3. One size does not fit all

Our main conclusion from the analysis conducted above is that the choice of a model description standard is purpose-dependent and that no single model description type alone can fulfil all requirements simultaneously. We have identified conflicting objectives: a) to achieve a detailed model description that enables model replication and b) to provide a concise and easy to communicate model description. Furthermore, one should avoid making the recommendations for model description more demanding than necessary for its purpose. This is important for making the recommendations useful to a wide range of authors, which seems to be a precondition for the establishment of a common standard of model description.

Although the provision of information (especially source code) is sometimes hindered by legal or other institutional reasons (Polhill and Edmonds, 2007, Ince et al., 2012), we consider it important to make the **source code** of a model available for two reasons: firstly, because it provides the most direct means of replicating model experiments, and secondly, because it is necessary to allow others to identify shortcomings in the implementation chosen by the author. The website www.openabm.org, for example, provides an archive where model files can be uploaded to share source code and/or model implementations.

Natural language description, especially when formalized in **standard protocols, such as ODD** (Grimm et al., 2010) or its extension focusing on human decision-making ODD+D,(Müller et al., 2013, , Chapter 6), helps to make a connection between verbal descriptions of the real world system underlying the model and the model itself. These standard protocols can inform the scientific community whether and how the model itself meets minimum scientific standards, and what additional aspects or capabilities the model requires to meet its specific purposes. In our view, the elements which should be documented in the protocol in order to meet a minimum standard of model description fall into two main categories: those that are always needed to describe any system models (e.g. goal statement, context/boundary setting conditions, unit and scale of analysis), and those that are specific for an ABM, such as minimal characteristics of the encoded agents (e.g. “heterogeneous”, “autonomous”, “interactive”, “reactive” and “adaptive”, Benenson and Torrens, 2004) or system properties that ABMs are usually designed to explain (e.g. “emergence” and “adaptation”, cf. Holland, 1995, Bonabeau, 2002).

Standard protocols tell authors the information they need to include in their model description, and they prime readers’ expectations regarding what information they will find where. For readers, this can facilitate the understanding of the assumptions made in the implementation of a model. It further requires authors to more fully open the “black box” of their model, potentially revealing its weak areas and better contributing to scientific progress. Therefore, we consider the use of a standard description important.

In addition, graphical representations, such as UML diagrams, can facilitate various purposes of model communication and understanding, and informal graphical representations are especially beneficial for educational purposes and when working with stakeholders. The close links between certain graphical representations and ontologies present a strong argument for the use of ontologies in the model design phase (cf. Livet et al., 2010, for the potential of ontologies for model building). However, the particular mode of graphical representation to use is sensitive to the model in question and to the intended audience. Hence, we do not recommend it as a minimum standard for model description in journal articles, but as an optional augmentation to the text and source code.

7.4. Ways ahead

We recommend that researchers build on current examples of good model descriptions, not only to describe their models transparently, but also to strive for common standards in describing ABMs, in order to contribute to comparability, model assessment and replication, and theory development. However, many open questions and challenges also remain, which need to be addressed to improve model descriptions in the future.

Firstly, the standardisation of model descriptions is impeded by the fact that it is extremely difficult to find a consistent terminology across the many disciplines to which agent-based modelling is applied (cf. Balbi and Giupponi, 2010). Researchers on multi- and inter-disciplinary projects often report that differences in terminology and vocabulary are an impediment to mutual understanding (McConnell et al., 2011). A standardised description has the potential to promote the use of a common terminology, through suggesting and defining terminology such as agent and emergence by a standardised description protocol, examples and guiding questions therein.

Secondly, while there is a lot of common understanding about the purposes of model descriptions, there are some aspects on which we have found different perspectives. A major issue is whether natural language description standards need to be detailed enough to allow for replication, or whether such standards should only facilitate understanding and communication, leaving replication to the availability of the source code. On the one hand, if we emphasize the view that natural language descriptions are necessary to assess the consistency between the model and the real world, then this might be an argument to make standardised descriptions comprehensive enough to allow for replication. On the other hand, the question arises of whether such comprehensive descriptions might come at the cost of losing the readability of the documentation when models are very large and/or complex. Solutions to this might come from hierarchical natural language description such the ODD (starting from an overview and providing details later) or distinguishing between different levels of replication (numerical, statistical, and qualitative) and from developing large models over the course of several articles (Polhill et al., 2008, Grimm et al., 2010). However, the debate has not yet come to a conclusion.

In addition, although we have focused on model descriptions in this article, there are similar challenges for the description of model results. One attempt to address this issue is the use of narrative approaches which, for a working model, can be useful to illustrate characteristic (and specific) interactions between model agents and explain how these interactions produce system-level dynamics (Millington et al., 2012). Information about model outputs may be relevant for theory building; for example, documentation about hypotheses tested by the model and their results, or the results of global sensitivity analysis.

Thirdly, there are institutional and cultural issues surrounding the adoption and spread of standards. Should authorities promote standards (e.g. by journals making them a publication requirement Polhill et al., 2010), or should they spread in an emergent process? Another aspect is that the pressure for providing transparent model descriptions might be greater if replicating a model to assess the reliability of its results were a more common practice in the ABM scientific arena. However, several institutional and cultural factors impede such a development: journals do not insist on licenses that enable software reuse, employers have an interest in protecting intellectual property rights, there are no standard libraries for ABM, and replication is not seen by everyone as innovative research. Further, model replication is a resource-intensive undertaking, and in an era of shrinking research budgets and university funding, it may not be practical.

Finally, there have been several attempts to ease communication between modellers and facilitate reuse of models and model components. Such reuse is seen as potentially decreasing start-up costs and reducing barriers to entry to modelling, thus increasing efficiency and speed of scientific progress in the field (Alessa et al., 2006). Common platforms for ABMs and model-level tools have been developed with these goals in mind. Contrary to program-level tools, model-level tools allow “the usage of ... simulation models without requiring programming. These are pre-programmed models, designed for specific application fields that can be parameterized by the user." (de Sousa and da Silva, 2011, p.170). The authors cite AnyLogic as an example (www.anylogic.com). Model-level tools can greatly facilitate communication since each model can be described simply by its set of parameters and inputs, using a single standard implementation. On the negative side this sort of tools tends to be highly specialised, filling narrow market niches; thus they are usually commercial tools whose internal implementation may not be open to independent scrutiny.

Although some platforms and program-level tools such as Repast have become popular, there are still a plethora of different platforms being used by the ABM developer community. The issue of how to increase research efficiency in the field by helping to facilitate code reuse remains an important one, but the large number of platforms impedes developments in this direction to some extent, and there seems to be no tendency towards agreeing on one common platform that is used by everyone. Therefore, we suggest it is worth working on a platform-independent standard for model description, especially as such a standard should remain relevant and useful even if common code bases are adopted in the future.

The process of establishing such a platform-independent standard for model descriptions could be inspired by successful attempts to establish standards in other domains: Model-Driven Development (Selic, 2003) is an emerging approach proposing the creation of domain specific lexica allowing for the simultaneous development and documentation of models. It has proved successful in domains parallel to ABM, notably with the SysML and ModelicaML languages, thus pointing to a further avenue for standardisation. To mention a second example, the Object Management Group (OMG) is a non-for-profit organisation of the software industry that has developed several widely adopted standards such as UML (UML, 2011), while over the years evolving a rather intricate internal structure with a multi-tier hierarchy and multiple ad-hoc boards at top level. A third example is the Open Geospatial Consortium (OGC), which involves the public sector, academia and industry to develop standards for spatial data publication and sharing (Castronova et al., 2013). These success stories highlight two points: First, some sort of formal and well-defined organisation is needed to drive the process of specification and later on the diffusion of the standard. Second, well-defined standards that address objective problems tend to be swiftly adopted by software developers and the industry in general. In the context of ABM, which is a domain still somewhat restricted to academia, an organisation like the OGC seems more suitable. This kind of organisation may be simpler for a small number of volunteers to start working on a draft standard, drawing on platforms such as www.openabm.org.

7.5. Conclusion

We have identified eight main purposes of model descriptions and summarized our expert knowledge in an assessment of the suitability of description types for different purposes. We conclude that no single model description type alone can fulfil all purposes simultaneously. Hence, we suggest a minimum standard consisting of a structured natural language description plus the provision of source code. Such description frame is particularly important for academic purposes, favouring in-depth model comprehension and model assessment. This echoes comments by other authors (Ince et al., 2012, Polhill and Edmonds, 2007) that good modelling practice entails both the provision of source code and an accessible natural language description, ideally following a formalized standard such as ODD (Grimm et al., 2006, 2010). However, other description types can strengthen model description substantially in regard to specific purposes or target groups. For instance, graphics are appropriate to facilitate the model communication, while ontologies can foster model comparison and mathematics can improve the possibilities of replication. Every author should therefore tailor the usage and weight of one or more description types according to the characteristics of the model and the purpose of the publication, in the view of meeting the above mentioned minimum standard. A joint effort of the ABM community towards transparent and comprehensible model descriptions through the use of standards would lead to a significant advancement of the field by enhancing exchange of information between peers and improving communication with model end-users. Therewith, the potential of agent-based modelling to support problem-oriented analysis and governance of human-natural systems would strongly increase.

Part IV.

Discussion and Synthesis

8. Discussion and Synthesis

This thesis started from the observation that multiple strategic goals are the reason for the political fostering of bioenergy production. These are security of energy supplies, independence from fossil fuels, climate change mitigation and additional generation of value in rural areas (Plieninger et al., 2006, WBGU, 2009, Gamborg et al., 2012). Our aim was to model the impact of the introduction of bioenergy on the land use system and to identify conditions under which bioenergy production can meet the strategic goals in a sustainable way. An additional aim was to present policy options to mitigate unwanted side effects of bioenergy production

Our approach was to conceptualize the bioenergy issue as a system with market demands and policies that are implemented in policy instruments as external drivers. These influence individual land use decisions, which cause changes of the land use patterns. The changes can be the cause of adverse side effects in the social and the ecological system. The land use patterns can be evaluated from multiple perspectives that represent the different strategic goals of bioenergy production. Different countermeasures can be tested for effectiveness when the strategic goals are missed.

For our analysis we designed an agent-based model (ABM). This type of model is particularly well suited to study the land use system (Matthews et al., 2007, Parker et al., 2008b, Rounsevell and Arneth, 2011, Filatova et al., 2013).

The structure of this chapter follows the approach of our analysis. We will start by a synthesis of our results concerning the change of land use patterns through the external drivers. In the subsequent section, we will discuss our findings with respect to the impacts of bioenergy production. The results from testing policy options to combat unwanted side effects of bioenergy production are presented in the next section. We conclude with reflections on our modeling approach and a synthesis of the methodological chapters on the documentation and communication of agent-based models.

8.1. Land use change through an increasing bioenergy demand

The land use change that is triggered by an increase of the bioenergy demand is still not fully understood, because of its complexity (comprising e.g. the interplay of different drivers, feedbacks and processes at different temporal and spatial scales FAO, 2009, WBGU, 2009, Witcover et al., 2013). Agent-based models allow to study these features of complex systems (Bousquet and Le Page, 2004, Filatova et al., 2013, Rounsevell et al., 2012). Especially in the context of the bioenergy issue, it is very important to understand the triggered land use change, because it is the reason of unwanted side effects of bioenergy production (Searchinger et al., 2008, Lapola et al., 2010, Engel et al., 2012). Therefore, the first aim of our analysis was to gain a mechanistic understanding of the land use change that is caused by an increasing bioenergy demand.

Our model results show that the land user agents react by changing their land use towards more bioenergy production when the bioenergy demand D^{BE} increases. This results in land use conflicts because land is limited. Land use conflicts have been widely described in the context of bioenergy production (an overview can be found in WBGU (2009)). Our modeling approach enables us to specify the framework conditions that lead to a specific form of land use conflict. In the model settings that we tested, an increase of the bioenergy demand initially caused a decline of areas that are not under cultivation which continued until they disappeared. At a specific bioenergy demand, the complete model region is used for cultivation of energy-, or other crops. When the bioenergy demand increases further, other agrarian production declines, indicating a shift of the type of the land use conflict in dependence from the height of D^{BE}.

In addition to the finding that different types of land use conflicts occur, we could characterize the functional response of the land use pattern to an increase of D^{BE}. We found that there is a critical D^{BE} value. Below this value the bioenergy harvest increases linearly with and increase of D^{BE}. Above the critical value, the harvests increase in a bell-shaped curve. In addition, below the critical D^{BE} value, all three land use forms are in the system (i.e. bioenergy, other agrarian production, cells that are not under cultivation). Above the value, all areas are under cultivation.
These results show the need to differentiate between moderate and high demands for bioenergy. If the demand is generated through policy actions, the strength of the incentive will determine its effect on areas that are not under cultivation, but may have other important functions (e.g. provision of ecosystem services MA, 2005, Sukhdev et al., 2010).

To conclude, an increasing bioenergy demand can lead to different forms of land use conflict. There is a need to take the economic framework conditions into account when the land use effects of bioenergy production are to be evaluated, because the type of land use conflict that occurs depends on them. The conditions may be regionally distinct, which highlights the need for regionally specific approaches of evaluation.

8.2. Climate impact of the land use change through an increasing bioenergy demand

In our impact analysis of bioenergy production we focused on the climate impact because it is intensely debated under which circumstances bioenergy is suited as a measure of climate change mitigation (WBGU, 2009, Searchinger et al., 2009, Searchinger,

2010, Chum et al., 2011, Haberl, 2013). This was operationalized by the analysis of a cumulative measure of all emissions and emission reductions during a simulation period (the atmospheric C-stock C^{Atm}).
One finding was that the question whether the political fostering of bioenergy has positive or negative impacts can not be answered in general, but is context dependent. From our model results we distinguished three possible climate effects of an increasing bioenergy demand D^{BE} (cf. Chapter 4):

1. Response Pattern I: C^{Atm} decreases with increasing D^{BE}, i.e. politically fostering bioenergy meets the goal of climate change mitigation.

2. Response Pattern II: C^{Atm} increases at low D^{BE} values and decreases at high D^{BE}, i.e. there is a risk that the climate change mitigation goal is missed.

3. Response Pattern III: C^{Atm} increases for the whole range of D^{BE} values, i.e. politically fostering fails to reach the goal of climate change mitigation.

Besides indicating under which circumstances bioenergy production meets the goal of climate change mitigation, these patterns indicate the need for policy action to counteract unwanted climate side effects.

The unintended side effects are caused by large emissions from the destruction of terrestrial C-stocks that can not be balanced through emission reductions by bioenergy during the reference period. This mechanism is also known as the “carbon debt” of bioenergy (Fargione et al., 2008, Achten and Verchot, 2011, Gelfand et al., 2011). Therefore, a prerequisite for unintended side effects are areas that are not under cultivation and function as ecosystem C-stocks. This is another indicator for the necessity of a regionally specific assessment of the effects of bioenergy production, because the amount of carbon that is stored in the vegetation is regionally distinct (Sitch et al., 2003).

This shows the crucial role of terrestrial C-stocks for the impact of bioenergy production (Chum et al., 2011, Gelfand et al., 2013, Haberl, 2013). The extent of areas that are not under cultivation is strongly determined by the economic framework conditions (cf. Chapter 3). Therefore, these conditions are relevant for the climate impact of bioenergy production as well. Interestingly, the climate effect of bioenergy also depends on the demands and production costs for other agrarian products (in addition to technological and economic framework conditions related to bioenergy). This complex connection between ecological and economic framework conditions affirms the usefulness of ecological economic modeling approaches (Liu et al., 2007, Parker et al., 2008b, Filatova et al., 2013).

We also found that there are factors that strengthen, respectively weaken the dependency of the climate effect of bioenergy production on the land use pattern. A high reduction of C-emissions through bioenergy (i.e. a high potential of the technology) decouples the climate effect of bioenergy from the land use pattern. This demonstrates that the assessment of the bioenergy issue needs to extend beyond an analysis of the triggered land use change (Elghali et al., 2007, Buchholz et al., 2009). However, this result also suggests that bioenergy can, in theory, be beneficial for the climate, although its introduction leads to the destruction of terrestrial C-stocks.

This observation demonstrates that interferences between different approaches to climate change mitigation may exist. In this case, there is a trade-off between climate change mitigation by the conservation of terrestrial C-stocks and by the substitution of fossil fuels through bioenergy. The results emphasize the need for an integrated view on the issue of climate change mitigation (Young et al., 2006) in order to avoid counterproductive combined effects.

8.3. The potential of policy instruments to counteract unwanted side-effects of the land use change through an increasing bioenergy demand

Agent-based models allow to extend beyond the traditional approach of modeling policy instruments "as a lever in land system models that can be pulled (exogenously) to explore alternative outcomes" (Rounsevell and Arneth, 2011) because they allow to study feedbacks between the policy outcome and the policy itself (Rounsevell and Arneth, 2011). Hence, agent-based models have often been used to test the impact of policy instruments (Berger, 2000, Happe et al., 2006, Kollmann and Page, 2006, Hartig and Drechsler, 2009, Filatova et al., 2011, Zhang et al., 2011, Polhill et al., 2013, Sun and Müller, 2013).
In Chapter 5 we used our model to compare the potential of differently designed, regionally optimized economic policy instruments to mitigate unwanted climate side effects of bioenergy production.

The policy instruments are designed to approach relevant strategies of climate change mitigation:

1. Stopping the formation of new C-emission sources by avoiding the destruction of ecosystem C-stocks

2. Fostering the creation of additional C-sinks by creating new ecosystem C-stocks

3. Avoiding permanent C-emissions

4. Fostering a decrease of the permanent C-emissions

The instruments function by setting financial incentives for land users to behave according to these strategies. However, the application of these policy instruments can

lead to new trade-offs. For instance instruments that set an incentive for land users to conserve their terrestrial C-stock instead of using their land for cultivation will lead to a reduction of the regional harvests (Ghazoul et al., 2010, Lambin and Meyfroidt, 2011, Smith et al., 2013). Our model results also showed this socio-economic side effect in the form of loss of areas under cultivation through the application of the policy instruments. Hence, the effort to mitigate one unwanted side effect of bioenergy production puts another strategic goal of bioenergy at stake, i.e. the additional generation of value in rural areas (Gamborg et al., 2012).
In order to deal with this trade-off we extended our analysis by this unintended socio-ecological side effect. Our approach was to introduce a constraint on the maximum loss of cells under cultivation. We could show that it is advantageous to adapt the instruments regionally: the instruments were calibrated so that their application leads to the maximum reduction of the atmospheric C-stock for a given tolerated loss of areas under cultivation.

Most of the optimized instrument types were useful to lower the atmospheric C-stock. When more loss of areas under cultivation is tolerated, the atmospheric C-stock can be lowered further to some extent. This shows that the extent of one unwanted side effect can be diminished at the cost of the increase of another unwanted side effect. Furthermore, there are limits to the maximum effectiveness of the policy instruments that are determined by the instruments design.

The most effective instruments were those that granted a payment for the conservation of terrestrial C-stocks. The instruments that set an incentive that is coupled to the C-sequestration were the least effective instruments. One reason is that the height of their incentive is determined by the C-stock that can grow within a single time step. This shows that it is important to consider the time span that is required by the ecosystem requires to provide the service that is of interest for the society. This insight was facilitated by the ability of ABMs to study fully coupled socio-ecological systems (Parker et al., 2008b).

Another problem is the interference of the effect of the policy instrument and the effect of bioenergy as a measure of climate change mitigation. When the potential of bioenergy to reduce C-emissions is very high, the application of effective policy instruments leads to an inferior climate outcome, compared to a situation without the instrument. The trade-off between climate change mitigation through technology and climate change mitigation through the conservation of terrestrial C-stocks appears in this case as well.

This is a noteworthy result, because the destruction of ecosystem C-stocks is not sustainable. Adverse effects can include the loss of biodiversity or the loss of ecosystem services that are not related to climate change mitigation (MA, 2005, Sukhdev et al., 2010). Therefore, climate protection is not necessarily leading to a win-win situation with the enhancement of other sustainability criteria. The potential for synergy is limited (Huston and Marland, 2003).

8.4. Reflection on our methodological approach

8.4.1. Insights that were facilitated by the design of our modeling framework

We choose to model the bioenergy issue with an ABM, because this method is well suited to study land use systems when the consequences of individual decisions and the coupling of the social and the ecological system are of interest (Hare and Deadman, 2004, Matthews et al., 2007, Parker et al., 2008b, Rounsevell and Arneth, 2011, Filatova et al., 2013). These properties are useful to model the bioenergy issue in order to understand the interplay between drivers of land use change, agent decisions and their socio-economic and ecological impacts.

Another advantage of agent-based models is that they allow to model the effects of various forms of heterogeneity (e.g. Jager et al., 2000, Happe et al., 2006, Acosta-Michlik and Espaldon, 2008, Filatova et al., 2011, Kelley and Evans, 2011, Murray-Rust et al., 2011).
In the example applications (Chapters 3,4,5), however, we did not make use of this potential. By assuming homogeneity among the agents regarding their cost functions, their decision models and the extent and quality of areas that they manage we provided a reference for further studies. The strategy is to systematically gain insights into the impacts of agent heterogeneity by contrasting the homogeneous with the heterogeneous model version.

This strategy of a stepwise analysis has yielded first results through two "satellite studies" that incorporated spatial heterogeneity (Sebestyen, 2012) and heterogeneity in the agents decision making (Nolzen, 2013) into the presented modeling framework. With these two associated "satellite studies" steps towards reality are made.
Both studies provide insights into the conditions under which heterogeneity between the agents does not have any effect, i.e. the social ecological system behaves as an equivalent homogeneous system with "average" agents. These conditions included e.g. the ranking of the performance of the policy instruments or the maximum climate impact of bioenergy production.
The studies also allow to characterize the conditions under which heterogeneity has extra effects (e.g. occurrence of path dependency leading to multiple market equilibria). However, these could only be revealed by comparison to the homogeneous reference.
The phenomenon that aggregate behavior of heterogeneous entities can equal the behavior of average agents is known from "mean field approaches" in ecology (Fahse et al., 1998, Frank and Wissel, 2002, Ovaskainen and Hanski, 2004).

Our homogeneity assumptions facilitated the comparison with the traditional microeconomic equilibrium approach (Mankiw and Taylor, 2006, Engelkamp and Sell, 2007). This enabled analytical considerations which could be analyzed in parallel with the simulation results. Results that were obtained, respectively understood through the analytical considerations include:

- The calculation of the harvests in the equilibrium H^{j*}
- The calculation of the atmospheric C-stock C^{Atm} at the end of the assessment period
- The functional relationship between the occurrence of the C^{Atm} - Response Patterns and the economic parameters
- The coupling and decoupling of climate change mitigation from/to the existence of cells that are not under cultivation
- Identification of the transformation costs as a parameter of interest (transformation costs are often neglected in economic models)

In a nutshell, the analytical considerations facilitated the approximation of functional system responses, the identification of key parameters and of interesting parameters for further model analysis. For future work the analytical considerations would also allow to generate hypothesis on the effects of up-, or downscaling (e.g. by changing the number of agents N).

The option to use analytical considerations to complement the simulation results is one of the advantages of stylized models. These models are characterized by the use of aggregation in order to reduce complexity. In our model, we aggregated processes as well as parameters.

An example for an aggregated parameter is the C-emission reduction through bioenergy (ϵ_L). Conceptually, it is the net climate benefit of bioenergy during its life cycle. ϵ_L includes characteristics within the land use system as well as outside the system boundaries.
Inside the land use system, it comprises the choice and quality of the energy crops (Adler et al., 2007, Sterner and Fritsche, 2011) and characteristics of the production chain. Outside the land use system, the type of fossil fuels which are substituted are of importance (Cherubini et al., 2009, Cherubini and Strømman, 2011). This depends on the characteristics of the energy system in the region where the bioenergy is used. Hence, ϵ_L allows to analyze the climate impact of bioenergy production with a land use model without the need to account for different aspects of the life cycle explicitly.

It is important to mention that we do not assume bioenergy to be C-neutral. This erroneous assumption is still widely spread in policies and research (Searchinger et al., 2009, Haberl et al., 2012). The climate change mitigation effect that we assume is caused by the replacement of fossil fuels with a worse C-balance than bioenergy (e.g.

hard, and lignite coal or unconventional oil).

Explicitly considering a climate benefit of bioenergy in our model has been crucial for the modeling of processes that are highly relevant in the bioenergy debate, e.g. the mechanism of the carbon debt of bioenergy (Fargione et al., 2008, Achten and Verchot, 2011, Gelfand et al., 2011). It also allowed to model the trade-off between climate change mitigation by bioenergy or by the conservation of ecosystem C-stocks. The high sensitivity of the system to ϵ_L has demonstrated the importance of evaluating bioenergy as a part of the energy system, which is also emphasized in literature (Cherubini and Strømman, 2011, Sterner and Fritsche, 2011).

8.4.2. Insights that were facilitated by the design of the analysis

Our model assessment consisted of several structured partial sensitivity analyses. A central methodological idea was the "nested sensitivity analysis" (see Chapters 4 and 5) of the land use patterns as well as of the functional response of the climate balance to an increasing bioenergy demand. This allowed to identify "Response Patterns" and "Pattern Maps". These aggregated results were useful for the further analysis to study the dependence of the system response on economic, ecological and technological framework conditions.
This approach allowed to characterize framework conditions under which an increasing bioenergy demand will have adverse climate side effects (i.e. a need for policy action exists). In addition, the approach allowed to study whether the need for additional policy action and the performance of policy instruments are regionally specific.

8.4.3. Improving the description of agent-based models

In this thesis we demonstrated the potential of agent-based models as a tool for system understanding and the generation of hypotheses. However, the ability of this method to "embrace complexity" (Tesfatsion, 2006) causes specific challenges concerning transparent model descriptions. Part III of this thesis deals with this issue.

In Chapter 6 we proposed an extension to a widely used structured description of agent-based models (i.e. the ODD protocol Grimm et al., 2006, 2010). The ODD protocol consists of three sections: Overview, Design Concepts and Details. Each of these sections contains concepts, respectively categories for which guiding questions are asked.
Our extension complements elements that are needed to describe how human decisions are modeled. These are categories concerning the "Theoretical and Empirical Background" as well as the "Individual Decision Making" in the Design Concepts section. In the Details section we added the concept of "Heterogeneity". By this protocol we hope to aid the description of human decision making in a more straightforward way

than it is possible with the original ODD protocol.

However, there are also other types of model descriptions than structured prescriptive structures like the ODD+D (i.e. non-structured natural language descriptions, graphics (formal and informal), ontologies, source code, pseudo code and mathematical descriptions). We characterized these in Chapter 7 and assessed their potential to meet different purposes of model descriptions (i.e. model communication, in-depth comprehension, model assessment, model development, model replication, model comparison, theory building and code generation).

We found that these different purposes entail conflicting objectives (i.e. a detailed description that enables model replication vs. a concise and easy to communicate description). Therefore, "One size does not fit all" (cf. Chapter 7). Hence, we suggested a minimum standard consisting of a structured natural language description and the provision of source code.

8.5. Outlook

The modeling approach that we presented allowed to model an analysis of the effects of bioenergy production along the entire "Driver-Pressure-Impact-Response Chain" (Smeets et al., 1999). For further work it would be interesting to pursue two different ways towards more realism: 1) Stepwise integration of heterogeneity, 2) Exchange of the stylized submodels with more detailed existent models.
Concerning way 1, steps have been made through the use of heterogeneity regarding the quality and size of the agents' cells (Sebestyen, 2012) and the introduction of variable decision models (Nolzen, 2013). In further studies, heterogeneity regarding the emission characteristics of the different land use options could be implemented.
Numerous studies conclude that bioenergy production should be governed towards an increased use of residual materials as a feedstock (Gawel and Ludwig, 2011, Haberl et al., 2012, Haberl, 2013, Witcover et al., 2013). It is possible to include this in future model extensions by assigning an ϵ_L to other agrarian products as well. This could be used to analyze the climate effects of the co-existence of different bioenergy pathways.

The design of ABMs that can interact through macro level emergent properties with other modeling techniques has been identified as a frontier (Heckbert et al., 2010, Rounsevell and Arneth, 2011). In the case of our modeling framework the land use patterns that emerge under specific economic and political framework conditions could be that macro level property. Therefore, one option to pursue way 2 could be to use existent models for the evaluation of these land use patterns with respect to e.g. biodiversity indicators (e.g. Engel et al., 2012) or realistic C-balances (Taubert et al., 2012).

Bibliography

(1985). IEEE standard for binary floating-point arithmetic.

(2009). Renewables directive 2009/28/ec.

(2011). UML infrastructure specification, v2.4.1.

Aalders, I. (2008). Modeling land-use decision behavior with bayesian belief networks. *Ecology & Society* **13**, online.

Achten, W. M. J. and Verchot, L. V. (2011). Implications of biodiesel-induced land-use changes for CO2 emissions: Case studies in Tropical America, Africa, and Southeast Asia. *Ecology & Society* **16**, online.

Acosta-Michlik, L. and Espaldon, V. (2008). Assessing vulnerability of selected farming communities in the Philippines based on a behavioural model of agent's adaptation to global environmental change. *Global Environmental Change* **18**, 554 – 563.

Adler, P. R., Grosso, S. J. D. and Parton, W. J. (2007). Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. *Ecological Applications* **17**, 675–691.

Alessa, L. N., Laituri, M. and Barton, M. (2006). An "all hands" call to the social science community: Establishing a community framework for complexity modeling using agent based models and cyberinfrastructure. *Journal of Artificial Societies and Social Simulation* **9**.

An, L. (2012). Modeling human decisions in coupled human and natural systems: Review of agent-based models. *Ecological Modelling* **229**, 25–36.

Arnell, N., Lowe, J., Brown, S., Gosling, S., Gottschalk, P., Hinkel, J., Lloyd-Hughes, B., Nicholls, R. J., Osborn, T., Osborne, T., Rose, G., Smith, P. and Warren, R. F. (2013). A global assessment of the effects of climate policy on the impacts of climate change. *Nature Climate Change* **3**, 512–519.

Arthur, W. B. (2006). Out-of-equilibrium economics and agent-based modeling. In L. Tesfatsion and K. Judd, eds., *Agent-based Computational Economics*, Handbook of Computational Economics. North Holland, Oxford, pages 1551 – 1564.

Balbi, S. and Giupponi, C. (2010). Agent-based modelling of socio-ecosystems: A methodology for the analysis of adaptation to climate change **2**, 17–38.

Balbi, S., Giupponi, C., Perez, P. and Alberti, M. (2013). A spatial agent-based model for assessing strategies of adaptation to climate and tourism demand changes in an alpine tourism destination. *Environmental Modelling & Software* **45**, 29 – 51.

Balmann, A. (1997). Farm-based modelling of regional structural change: A cellular automata approach. *European Review of Agricultural Economics* **24**, 85–108.

Bardi, U. (2011). The political debate. In *The Limits to Growth Revisited*, SpringerBriefs in Energy. Springer New York. ISBN 978-1-4419-9415-8, pages 85–94.

Baron, J. (2000). *Thinking and Deciding*. Cambridge, MA: Cambridge University Press.

Barua, S. K., Uusivuori, J. and Kuuluvainen, J. (2012). Impacts of carbon-based policy instruments and taxes on tropical deforestation. *Ecological Economics* **73**, 211–219.

Becu, N., Perez, P., Walker, A., Barreteau, O. and Page, C. L. (2003). Agent based simulation of a small catchment water management in northern Thailand: description of the CATCHSCAPE model. *Ecological Modelling* **170**, 319–331.

Benenson, I. and Torrens, P. M. (2004). *Automata-based Modeling of Urban Phenomena*. Wiley, New York.

Bennett, D. A. and Tang, W. (2009). GAIA-RM: A geographically aware intelligent agents framework for rangeland management. In *10th International Conference on Geocomputation, University of New South Wales, Sydney, Australia.*

Berger, T. (2000). Agent-based spatial models applied to agriculture: A simulation tool for technology diffusion, resource use changes and policy analysis. *Agricultural Economics* **25**, 245–260.

Bersini, H. (2012). UML for ABM. *Journal of Artificial Societies and Social Simulation* **15**, online.

Bonabeau, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences of the United States of America* **99**, 7280–7287.

Boone, R. B., Galvin, K. A., BurnSilver, S. B., Thornton, P. K., Ojima, D. S. and Jawson, J. R. (2011). Using coupled simulation models to link pastoral decision making and ecosystem services. *Ecology and Society* **16**, online.

Bousquet, F. and Le Page, C. (2004). Multi-agent simulations and ecosystem management: a review. *Ecological Modelling* **176**, 313–332.

Brenner, T. (2006). Agent learning representation - advice in modelling economic learning. In L. Tesfatsion and K. Judd, eds., *Agent-based Computational Economics*, Handbook of Computational Economics. North Holland, Oxford, pages 895–947.

Buchholz, T., Rametsteiner, E., Volk, T. A. and Luzadis, V. A. (2009). Multi criteria analysis for bioenergy systems assessments. *Energy Policy* **37**, 484 – 495.

Busch, J., Lubowski, R. N., Godoy, F., Steininger, M., Yusuf, A. A., Austin, K., Hewson, J., Juhn, D., Farid, M. and Boltz, F. (2012). Structuring economic incentives to reduce emissions from deforestation within Indonesia. *Proceedings of the National Academy of Sciences* **109**, 1062–1067.

Butler, R. A., Koh, L. P. and Ghazoul, J. (2009). REDD in the red: palm oil could undermine carbon payment schemes. *Conservation Letters* **2**, 67–73.

Caillault, S., Mialhe, F., Vannier, C., Delmotte, S., Kêdowidé, C., Amblard, F., Etienne, M., Bécu, N., Gautreau, P. and Houet, T. (2012). Influence of incentive networks on landscape changes: A simple agent-based simulation approach. *Environmental Modelling & Software* , 64–73.

Camerer, C. F. and Loewenstein, G. (2004). Behavioral economics: Past, present, future. In C. Camerer, G. Loewenstein and M. Rabin, eds., *Advances in Behavioral Economics*. Princeton UP, Princeton, pages 3–51.

Caron-Lormier, G., Humphry, R. W., Bohan, D. A., Hawes, C. and Thorbek, P. (2008). Asynchronous and synchronous updating in individual-based models. *Ecological Modelling* **212**, 522–527.

Castella, J., Trung, T. and Boissau, S. (2005). Participatory simulation of land-use changes in the northern mountains of Vietnam: the combined use of an agent-based model, a role-playing game, and a geographic information system. *Ecology & Society* **10**, online.

Castronova, A. M., Goodall, J. L. and Elag, M. M. (2013). Models as web services using the open geospatial consortium (OGC) web processing service (WPS) standard. *Environmental Modelling & Software* **41**, 72–83.

Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B. and Woess-Gallasch, S. (2009). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling* **53**, 434 – 447.

Cherubini, F. and Strømman, A. H. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology* **102**, 437 – 451.

Christley, S., Xiang, X. and Madey, G. (2004). An ontology for agent-based modeling and simulation. In *Proceedings of the Agent 2004 Conference*. Citeseer.

Chum, H., Faaji, A., Moreira, G., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, A., Lucht, W., Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T. and Pingoud, K. (2011). Bioenergy. In P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer and C. von Stechow, eds., *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge UP, Cambridge.

Clifford, N. J. (2008). Models in geography revisited. *Geoforum* **39**, 675–686.

Corbera, E. and Schroeder, H. (2011). Governing and implementing REDD+. *Environmental Science & Policy* **14**, 89–99.

Davis, C., Nikolic, I. and Dijkema, G. P. J. (2009). Integration of Life Cycle Assessment Into Agent-Based Modeling. *Journal of Industrial Ecology* **13**, 306–325.

de Sousa, L. and da Silva, A. (2011). Review of spatial simulation tools for geographic information systems. In *SIMUL 2011, The Third International Conference on Advances in System Simulation*.

Deadman, P., Robinson, D., Moran, E. and Brondizio, E. (2004). Colonist household decisionmaking and land-use change in the Amazon rainforest: an agent-based simulation. *Environment and Planning B-Planning & Design* **31**, 693–709.

Deadman, P., Schlager, E. and Gimblett (2000). Simulating common pool resource management experiments with adaptive agents employing alternate communication routines. *Journal of Artificial Societies and Social Simulation* **3**, online.

Dibble, C. (2006). Computational laboratories for spatial agent-based models. In L. Tesfatsion and K. L. Judd, eds., *Handbook of Computational Economics, Volume 2: Agent-Based Computational Economics, Handbooks in Economics*. North-Holland, Oxford, pages 1511–1548.

Don, A., Osborne, B., Hastings, A., Skiba, U., Carter, M. S., Drewer, J., Flessa, H., Freibauer, A., Hyvonen, N., Jones, M. B., Lanigan, G. J., Mander, U., Monti, A., Djomo, S. N., Valentine, J., Walter, K., Zegada-Lizarazu, W. and Zenone, T. (2012). Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon. *Global Change Biology Bioenergy* **4**, 372–391.

Duffy, J. (2001). Learning to speculate: Experiments with artificial and real agents. *Journal of Economic Dynamics & Control* **25**, 295 –319.

Eden, C. (1988). Cognitive mapping. *European Journal of Operational Research* **36**, 1–13.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, P., Eickemeier, P., Hansen, G., Schlömer, S. and

von Stechow, C. (2011). Summary for policymakers. In P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer and C. von Stechow, eds., *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, pages 3–26.

Eggers, J., Trölitsch, K., Falcucci, A., Maiorano, L., Verburg, P. H., Framstad, E., Louette, G., Maes, D., Nagy, S., Ozinga, W. et al. (2009). Is biofuel policy harming biodiversity in europe? *Global Change Biology Bioenergy* **1**, 18–34.

Elghali, L., Clift, R., Sinclair, P., Panoutsou, C. and Bauen, A. (2007). Developing a sustainability framework for the assessment of bioenergy systems. *Energy Policy* **35**, 6075 – 6083.

Engel, J., Huth, A. and Frank, K. (2012). Bioenergy production and skylark *(Alauda arvensis*) population abundance - a modelling approach for the analysis of land-use-change impacts and conservation options. *Global Change Biology Bioenergy* **4**, 713–727.

Engel, S., Pagiola, S. and Wunder, S. (2008). Designing payments for environmental services in theory and practice: An overview of the issues. *Ecological Economics* **65**, 663–674.

Engelkamp, P. and Sell, F. (2007). *Einführung in die Volkswirtschaftslehre*. Springer, Heidelberg.

Epstein, J. M. (2006). Remarks on the foundation of agent-based generative social science. In L. Tesfatsion and K. Judd, eds., *Agent-based Computational Economics*. North Holland, Oxford, pages 1586 – 1604.

Epstein, J. M. (2008). Why model? *Journal of Artificial Societies and Social Simulation* **11**, online.

Erb, K.-H., Haberl, H. and Plutzar, C. (2012). Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy* **47**, 260–269.

Fahse, L., Wissel, C. and Grimm, V. (1998). Reconciling classical and individual-based approaches in theoretical population ecology: a protocol for extracting population parameters from individual-based models. *The American Naturalist* **152**, 838–852.

FAO (2008). *The State of Agricultural Commodity Markets: Biofuels: Prospects, Risks and Opportunities*. FAO, Rome.

FAO (2009). *The State of Agricultural Commodity Markets: High Food Prices and the Food Crisis - Experiences and Lessons Learned*. FAO, Rome.

Fargione, J., Hill, J., Tilman, D., Polaksy, S. and Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science* **319**, 1235–1238.

Feola, G. and Binder, C. R. (2010). Towards an improved understanding of farmers' behaviour: The integrative agent-centred (IAC) framework. *Ecological Economics* **69**, 2323–2333.

Filatova, T., Parker, D. and van der Veen, A. (2009). Agent-based urban land markets: Agent's pricing behavior, land prices and urban land use change. *Journal of Artificial Societies and Social Simulation* **12**, online.

Filatova, T., Verburg, P. H., Parker, D. C. and Stannard, C. A. (2013). Spatial agent-based models for socio-ecological systems: Challenges and prospects. *Environmental Modelling & Software* **45**, 1 – 7.

Filatova, T., Voinov, A. and van der Veen, A. (2011). Land market mechanisms for preservation of space for coastal ecosystems: An agent-based analysis. *Environmental Modelling & Software* **26**, 179–190.

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Chapin, T. and Rockström, J. (2010). Resilience thinking: integrating resilience, adaptability and transformability. *Ecology & Society* **15**, Art. no. 20 (online).

Frank, K. and Wissel, C. (2002). A formula for the mean lifetime of metapopulations in heterogeneous landscapes. *The American Naturalist* **159**, 530–552.

Gamborg, C., Millar, K., Shortall, O. and Sandoe, P. (2012). Bioenergy and land use: Framing the ethical debate. *Journal of Agricultural & Environmental Ethics* **25**, 909–925.

Gawel, E. and Ludwig, G. (2011). The iLUC dilemma: How to deal with indirect land use changes when governing energy crops? *Land Use Policy* **28**, 846–856.

GEA (2012). *Global Energy Assessment - Toward a Sustainable Future*. Cambridge UP, Cambridge.

Geist, H. J. and Lambin, E. (2002). Proximate causes and underlying driving forces of tropical deforestation. *Bioscience* **52**, 143–150.

Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R. C., Gross, K. L. and Robertson, G. P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. *Nature* **493**, 514–517.

Gelfand, I., Zenone, T., Jasrotia, P., Chen, J., Hamilton, S. K. and Robertson, G. P. (2011). Carbon debt of conservation reserve program (CRP) grasslands converted to bioenergy production. *Proceedings of the National Academy of Sciences* **108**, 13864–13869.

Ghazoul, J., Butler, R., Mateo-Vega, J. and Pin Koh, L. (2010). REDD: A reckoning of environment and development implications. *Trends in Ecology & Evolution* **25**, 369–402.

Gigerenzer, G. and Selten, R. (2001). *Bounded Rationality - the Adaptive Toolbox*. MIT Press.

Gilberg, R. F. and Forouzan, B. A. (2004). *Data Structures: A pseudocode approach with C*. Cengage Learning, UK.

Gotts, N. M., Polhill, J. G. and Law, A. N. R. (2003). Agent-based simulation in the study of social dilemmas. *Artificial Intelligence Review* **19**, 3–92.

Grau, B. C., Horrocks, I., Motik, B., Parsia, B., Patel-Schneider, P. and Sattler, U. (2008). OWL 2: The next step for OWL. *Web Semantics: Science, Services and Agents on the World Wide Web* **6**, 309–322.

Grimm, V., Berger, U., Bastiansen, F., Eliassen, S., Ginot, V., Giske, J., Goss-Custard, J., Grand, T., Heinz, S., Huse, G., Huth, A., Jepsen, J., Jorgensen, C., Mooij, W., Muller, B., Pe'er, G., Piou, C., Railsback, S., Robbins, A., Robbins, M., Rossmanith, E., Ruger, N., Strand, E., Souissi, S., Stillman, R., Vabo, R., Visser, U. and Deangelis, D. (2006). A standard protocol for describing individual-based and agent-based models. *Ecological Modelling* **198**, 115–126.

Grimm, V., Berger, U., DeAngelis, D. L., Polhill, J. G., Giske, J. and Railsback, S. F. (2010). The ODD protocol: A review and first update. *Ecological Modelling* **221**, 2760 – 2768.

Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., Railsback, S. F., Thulke, H.-H., Weiner, J., Wiegand, T. and DeAngelis, D. L. (2005). Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science* **310**, 987–991.

Gruber, T. R. et al. (1993). A translation approach to portable ontology specifications. *Knowledge acquisition* **5**, 199–220.

Haase, D., Lautenbach, S. and Seppelt, R. (2010). Modeling and simulating residential mobility in a shrinking city using an agent-based approach. *Environmental Modelling & Software* **25**, 1225–1240.

Haberl, H. (2013). Net land-atmosphere flows of biogenic carbon related to bioenergy: towards an understanding of systemic feedbacks. *Global Change Biology Bioenergy* **5**, 351–357.

Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Mueller, C., Plutzar, C. and Steinberger, J. K. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. *Biomass & Bioenergy* **35**, 4753–4769.

Haberl, H., Sprinz, D., Bonazountas, M., Cocco, P., Desaubies, Y., Henze, M., Hertel, O., Johnson, R. K., Kastrup, U., Laconte, P., Lange, E., Novak, P., Paavola, J., Reenberg, A., van den Hove, S., Vermeire, T., Wadhams, P. and Searchinger, T. (2012). Correcting a fundamental error in greenhouse gas accounting related to bioenergy. *Energy Policy* **45**, 18–23.

Hanau, A. (1928). Die Prognose der Schweinepreise, Vierteljahreshefte zur Konjunkturforschung. *Verlag Reimar Hobbing, Berlin* .

Happe, K., Kellermann, K. and Balmann, A. (2006). Agent-based analysis of agricultural policies: an illustration of the agricultural policy simulator agripolis, its adaptation and behavior. *Ecology & Society* **11**.

Hare, M. and Deadman, P. (2004). Further towards a taxonomy of agent-based simulation models in environmental management. *Mathematics and Computers in Simulation* **64**, 25 – 40.

Hartig, F. and Drechsler, M. (2009). Smart spatial incentives for market-based conservation. *Biological Conservation* **142**, 779–788.

Heckbert, S., Baynes, T. and Reeson, A. (2010). Agent-based modeling in ecological economics. *Annals of the New York Academy of Sciences* **1185**, 39–53.

Holland, J. H. (1995). *Hidden order: How adaptation builds complexity*. Addison-Wesley, Reading, MA.

Horrocks, I., Patel-Schneider, P. F. and Van Harmelen, F. (2003). From SHIQ and RDF to OWL: The making of a web ontology language. *Web semantics: science, services and agents on the World Wide Web* **1**, 7–26.

Huston, M. A. and Marland, G. (2003). Carbon management and biodiversity. *Journal of Environmental Management* **67**, 77–86.

Ince, D. C., Hatton, L. and Graham-Cumming, J. (2012). The case for open computer programs. *Nature* **482**, 485–488.

IPCC (2007). Climate change 2007: synthesis report. Technical report, Intergovernmental Panel on Climate Change.

Jager, W., Janssen, M., De Vries, H., De Greef, J. and Vlek, C. (2000). Behaviour in commons dilemmas: Homo economicus and homo psychologicus in an ecological-economic model. *Ecological Economics* **35**, 357–379.

Jager, W. and Mosler, H. J. (2007). Simulating human behavior for understanding and managing environmental resource use. *Journal of Social Issues* **63**, 97–116.

Janssen, M. and Ostrom, E. (2006a). Governing social-ecological systems. In L. Tesfatsion and K. Judd, eds., *Agent-based Computational Economics*, volume 2 of *Handbook of Computational Economics*. North Holland, Oxford, pages 1466 – 1513. Chapter 30.

Janssen, M. A. (2009). Understanding artificial Anasazi. *Journal of Artificial Societies and Social Simulation* **12**, 13.

Janssen, M. A. and Ostrom, E. (2006b). Empirically based,agent-based models. *Ecology & Society* **11**.

Janssen, M. A., Walker, B. H., Langridge, J. and Abel, N. (2000). An adaptive agent model for analysing co-evolution of management and policies in a complex rangeland system. *Ecological Modelling* **131**, 249–268.

Jensen, F. V. (2001). Bayesian networks and decision graphs. Statistics for engineering and information science. *Springer* **32**, 34.

Johnson, J. G. and Busemeyer, J. R. (2010). Decision making under risk and uncertainty. *Wiley Interdisciplinary Reviews: Cognitive Science* **1**, 736–749.

Kahneman, D. (2003). A perspective on judgment and choice: mapping bounded rationality. *The American psychologist* **58**, 697–720.

Kelley, H. and Evans, T. (2011). The relative influences of land-owner and landscape heterogeneity in an agent-based model of land-use. *Ecological Economics* **70**, 1075 – 1087.

Killeen, T. J., Schroth, G., Turner, W., Harvey, C. A., Steininger, M. K., Dragisic, C. and Mittermeier, R. A. (2011). Stabilizing the agricultural frontier: Leveraging REDD with biofuels for sustainable development. *Biomass and Bioenergy* **35**.

Kitchin, R. M. (1994). Cognitive maps: What are they and why study them? *Journal of Environmental Psychology* **14**, 1–19.

Klassert, C., Frank, K. and Thrän, D. (2013). Transregional land-use dynamics of bioenergy policies: An agent-based approach. In *10th Biennal Conference of the European Society for Ecological Economics "Ecological Economics and Institutional Dynamics"*.

Knuth, D. (1984). Literate programming. *Computer Journal* **27**, 97–111.

Kollmann, K. and Page, S. (2006). Computational methods and models of politics. In L. Tesfatsion and K. Judd, eds., *Agent-based Computational Economics*, volume 2. Elsevier B.V., pages 1434–1461. Chapter 29.

Lambin, E. F. and Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* **108**, 3465–3472.

Lange, M. (2011). The GHG balance of biofuels taking into account land use change. *Energy Policy* **39**, 2373–2385.

Lapola, D. M., Schaldach, R., Alcamo, J., Bondeau, A., Koch, J., Koelking, C. and Priess, J. A. (2010). Indirect land-use changes can overcome carbon savings from biofuels in Brazil. *Proceedings of the National Academy of Sciences* **107**, 3388–3393.

Lautenbach, S., Volk, M., Strauch, M., Whittaker, G. and Seppelt, R. (2013). Optimization-based trade-off analysis of biodiesel crop production for managing an agricultural catchment. *Environmental Modelling & Software* **48**, 98 – 112.

Le, Q. B., Seidl, R. and Scholz, R. W. (2012). Feedback loops and types of adaptation in the modelling of land-use decisions in an agent-based simulation. *Environmental Modelling & Software* **27-28**, 83–96.

Liu, J. G., Dietz, T., Carpenter, S. R., Folke, C., Alberti, M., Redman, C. L., Schneider, S. H., Ostrom, E., Pell, A. N., Lubchenco, J., Taylor, W. W., Ouyang, Z. Y., Deadman, P., Kratz, T. and Provencher, W. (2007). Coupled human and natural systems. *Ambio* **36**, 639–649.

Livet, P., Müller, J.-P., Phan, D. and Sanders, L. (2010). Ontology, a mediator for agent-based modeling in social science. *Journal of Artificial Societies and Social Simulation* **13**, online.

Lotze-Campen, H., Popp, A., Beringer, T., Mueller, C., Bondeau, A., Rost, S. and Lucht, W. (2010). Scenarios of global bioenergy production: The trade-offs between agricultural expansion, intensification and trade. *Ecological Modelling* **221**, 2188–2196.

Luke, S., Cioffi-Revilla, C., Panait, L., Sullivan, K. and Balan, G. (2005). MASON: A multiagent simulation environment. *Simulation* **81**, 517–527.

Lux, T. and Marchesi, M. (1999). Scaling and criticality in a stochastic multi-agent model of a financial market. *Nature* **397**, 498–500.

MA (2005). *Millennium Ecosystem Assessment: Ecosystems and Human Well-being. Synthesis.* Island Press.

Mankiw, N. and Taylor, M. (2006). *Economics.* Thomson Learning, Toronto.

Marohn, C., Schreinemachers, P., Quang, D. V., Berger, T., Siripalangkanont, P., Nguyen, T. T. and Cadisch, G. (2013). A software coupling approach to assess low-cost soil conservation strategies for highland agriculture in Vietnam. *Environmental Modelling & Software* **45**, 116 – 128.

Maruyama, M. (1992). A quickly understandable notation system for causal loops for strategic decision makers. *Technological Forecasting and Social Change* **42**, 409–412.

Matthews, R. (2006). The people and landscape model (PALM): Towards full integration of human decision-making and biophysical simulation models. *Ecological Modelling* **194**, 329–343.

Matthews, R. B., Gilbert, N. G., Roach, A., Polhill, J. G. and Gotts, N. M. (2007). Agent-based land-use models: a review of applications. *Landscape Ecology* **22**, 1447–1459.

McAllister, R. R. J., Gordon, I. J., Janssen, M. A. and Abel, N. (2006). Pastoralists' responses to variation of rangeland resources in time and space. *Ecological Applications* **16**, 572–583.

McConnell, W., Millington, J., Alberti, M., Asbjornsen, H., Baker, L. A., Brozovic, N., Drinkwater, L. E., Drzyzga, S. A., Jantz, C. A., Fragoso, J., Holland, D. S., Kohler, T. T. A., Monticino, M., Podesta, G., Pontius, R., Redman, C., Sailor, D., Urquhart, G. and Liu, J. (2011). Research on coupled human and natural systems (CHANS): Approach, challenges, and strategies. *Bulletin of the Ecological Society of America* **92**, 218–228.

Millington, J. D., O'Sullivan, D. and Perry, G. L. (2012). Model histories: Narrative explanation in generative simulation modelling. *Geoforum* **43**, 1025–1034.

Millington, J. D. A., Romero-Calcerrada, R., Wainwright, J. and Perry, G. (2008). An agent-based model of Mediterranean agricultural land-use/cover change for examining wildfire risk. *Journal of Artificial Societies and Social Simulation* **11**, online.

Milner-Gulland, E. (2011). Integrating fisheries approaches and household utility models for improved resource management. *Proceedings of the National Academy of Sciences* **108**, 1741–1746.

Müller, B., Bohn, F., Dreß ler, G., Groeneveld, J., Klassert, C., Martin, R., Schlüter, M., Schulze, J., Weise, H. and Schwarz, N. (2013). Describing human decisions in agent-based models – ODD + D, an extension of the ODD protocol. *Environmental Modelling & Software* **48**, 37 – 48.

Murray-Rust, D., Dendoncker, N., Dawson, T. P., Acosta-Michlik, L., Karali, E., Guillem, E. and Rounsevell, M. (2011). Conceptualising the analysis of socio-ecological systems through ecosystem services and agent-based modelling. *Journal of Land Use Science* **6**, 83–99.

Nolzen, H. (2013). *Impact of Human Decision-Making on Land Use Change - Insights from an Agent-based Model*. Master's thesis, Universität Osnabrück.

North, M. J., Howe, T. R., Collier, N. T. and Vos, J. R. (2007). A declarative model assembly infrastructure for verification and validation. In *Advancing social simulation: the first world congress*. Springer.

Odum, E. P. (1969). The strategy of ecosystem development. *Science* **164**, 262–270.

Ostrom, E., G. R. W. J. (1994). *Rules, Games and Common Pool Resources*. University of Michigan Press, Ann Arbor.

Ovaskainen, O. and Hanski, I. (2004). From individual behavior to metapopulation dynamics: unifying the patchy population and classic metapopulation models. *The American Naturalist* **164**, 364–377.

Pahl-Wostl, C. and Ebenhöh, E. (2004). An adaptive toolbox model: a pluralistic modelling approach for human behavior based on observation. *Journal of Artificial Societies and Social Simulation* **7**, online.

Parker, D. (1999). Landscape outcomes in a model of edge-effect externalities: A computational economics approach. Technical report, Santa Fe Institute.

Parker, D., Manson, S., Janssen, M., Hoffmann, M. and Deadman, P. (2003). Multi-agent systems for the simulation of land-use and land-cover change: A review. *Annals of the Association of American Geographers* **93**, 314–337.

Parker, D. C., Brown, D. G., Polhill, J. G., Deadman, P. J. and Manson, S. M. (2008a). Illustrating a new "conceptual design pattern" for agent-based models and land use via five case studies: the MR POTATOHEAD framework. In A. L. Paredes and C. H. Iglesias, eds., *Agent-based modelling in natural resource management*. Valladolid, Spain: Universidad de Valladolid, pages 23–51.

Parker, D. C. and Filatova, T. (2008). A conceptual design for a bilateral agent-based land market with heterogeneous economic agents. *Computers, Environment and Urban Systems* **32**, 454 – 463.

Parker, D. C., Hessl, A. and Davis, S. C. (2008b). Complexity, land-use modeling, and the human dimension: Fundamental challenges for mapping unknown outcome spaces. *Geoforum* **39**, 789–804.

Perez, L. and Dragicevic, S. (2010). Modeling mountain pine beetle infestation with an agent-based approach at two spatial scales. *Environmental Modelling & Software* **25**, 223–236.

Persson, U. M. (2012). Conserve or convert? Pan-tropical modeling of REDD-bioenergy competition. *Biological Conservation* **146**, 81–88.

Phelps, J., Friess, D. and Webb, E. (2012). Win-win REDD+ approaches belie carbon-biodiversity trade-offs. *Biological Conservation* **154**, 53–60.

Plieninger, T., Bens, O. and Huttl, R. (2006). Perspectives of bioenergy for agriculture and rural areas. *Outlook on Agriculture* **35**, 123–127.

Polasky, S., Carpenter, S. R., Folke, C. and Keeler, B. (2011). Decision-making under great uncertainty: environmental management in an era of global change. *Trends in Ecology & Evolution* **26**, 398–404.

Polhill, G. and Izquierdo, L. (2005). Lessons learned from converting the artificial stock market to interval arithmetic. *Journal of Artificial Societies and Social Simulation* **8**.

Polhill, J., Parker, D. and Gotts, N. (2005). Introducing land markets to agent based models of land use change. In *Representing Social Reality: Preproceedings of the Third Conference of the European Social Simulation Association.*

Polhill, J. G. and Edmonds, B. (2007). Open access for social simulation. *Journal of artificial societies and social simulation* **10**, online.

Polhill, J. G., Gimona, A. and Gotts, N. M. (2013). Nonlinearities in biodiversity incentive schemes: A study using an integrated agent-based and metacommunity model. *Environmental Modelling & Software* **45**, 74 – 91.

Polhill, J. G. and Gotts, N. (2009). Ontologies for transparent integrated human-natural system modelling. *Landscape Ecology* **24**, 1255–1267.

Polhill, J. G., Parker, D., Brown, D. and Grimm, V. (2008). Using the ODD protocol for describing three agent-based social simulation models of land-use change. *Journal of Artificial Societies and Social Simulation* **11**, online.

Polhill, J. G., Sutherland, L.-A. and Gotts, N. M. (2010). Using qualitative evidence to enhance an agent-based modelling system for studying land use change. *Journal of Artificial Societies and Social Simulation* **13**.

Quaas, M. F., Baumgärtner, S., Becker, C., Frank, K. and Müller, B. (2007). Uncertainty and sustainability in the management of semi-arid rangelands. *Ecological Economics* **62**, 251–266.

Quinlan, J. (1986). Introduction of decision trees. *Machine Learning* **1**, 81–106.

Rebaudo, F. and Dangles, O. (2013). An agent-based modeling framework for integrated pest management dissemination programs. *Environmental Modelling & Software* **45**, 141 – 149.

Richiardi, M., Leombruni, R., Saam, N. J. and Sonnessa, M. (2006). A common protocol for agent-based social simulation. *Journal of Artificial Societies and Social Simulation* **9**, online.

Ricker, W. (1954). Stock and recruitment. *Journal of the Fisheries Research Board of Canada* **11**, 559–623.

Robinson, D. T., Sun, S., Hutchins, M., Riolo, R. L., Brown, D. G., Parker, D. C., Filatova, T., Currie, W. S. and Kiger, S. (2013). Effects of land markets and land management on ecosystem function: A framework for modelling exurban land-change. *Environmental Modelling & Software* **45**, 129 – 140.

Rounsevell, M. D., Pedroli, B., Erb, K.-H., Gramberger, M., Busck, A. G., Haberl, H., Kristensen, S., Kuemmerle, T., Lavorel, S., Lindner, M. et al. (2012). Challenges for land system science. *Land Use Policy* **29**, 899–910.

Rounsevell, M. D. A. and Arneth, A. (2011). Representing human behaviour and decisional processes in land system models as an integral component of the earth system. *Global Environmental Change* **21**, 840–843.

Roy, G. (2006). Designing and explaining programs with a literate pseudo-code. *Journal on Educational Resources in Computing* **6**, 1.

Satake, A., Leslie, H., Iwasa, Y. and Levin, S. (2007). Coupled ecological-social dynamics in a forested landscape: Spatial interactions and information flow. *Journal of Theoretical Biology* **246**, 695–707.

Scheffran, J. and BenDor, T. (2009). Bioenergy and land use: a spatial-agent dynamic model of energy crop production in Illinois. *International Journal of Environment and Pollution* **39**, 4–27.

Scheffran, Jürgen und BenDor, T. u. W. Y. u. H. B. (2007). A spatial-dynamic model of bioenergy crop introduction in llinois.

Schlüeter, M., McAllister, R. R. J., Arlinghaus, R., Bunnefeld, N., Eisenack, K., Hoelker, F., Milner-Gulland, E., Müller, B., Nicholson, E., Quaas, M. et al. (2012). New horizons for managing the environment: a review of coupled social-ecological systems modeling. *Natural Resource Modeling* **25**, 219–272.

Schlüter, M. and Pahl-Wostl, C. (2007). Mechanisms of resilience in common-pool resource management systems: an agent-based model of water use in a river basin. *Ecology & Society* **12**, online.

Schlüter, M., Savitsky, A., McKinney, D. and Lieth, H. (2005). Optimizing long-term water allocation in the Amudarya river delta: a water management model for ecological impact assessment. *Environmental Modelling & Software* **20**, 529–545.

Schmolke, A., Thorbek, P., Chapman, P. and Grimm, V. (2010a). Ecological models and pesticide risk assessment: current modeling practice. *Environmental Toxicology and Chemistry* **29**, 1006–1012.

Schmolke, A., Thorbek, P., DeAngelis, D. L. and Grimm, V. (2010b). Ecological models supporting environmental decision making: a strategy for the future. *Trends in Ecology & Evolution* **25**, 479–486.

Schreinemachers, P. and Berger, T. (2006). Land use decisions in developing countries and their representation in multi-agent systems. *Journal of Land Use Science* **1**, 29 – 44.

Schreinemachers, P. and Berger, T. (2011). An agent-based simulation model of human-environment interactions in agricultural systems. *Environmental Modelling & Software* **In Press, Corrected Proof**, –.

Scrieciu, S., T., B. and F., A. (2013). Pushing the boundaries of climate economics: critical issues to consider in climate policy analysis. *Ecological Economics* **85**, 155 – 165.

Searchinger, T., Heimlich, R., Houghton, R., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. and Yu, T.-H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* , 1238–1240.

Searchinger, T. D. (2010). Biofuels and the need for additional carbon. *Environmental Research Letters* **5**.

Searchinger, T. D., Hamburg, S. P., Melillo, J., Chameides, W., Havlik, P., Kammen, D. M., Likens, G. E., Lubowski, R. N., Obersteiner, M., Oppenheimer, M., Robertson, G. P., Schlesinger, W. H. and Tilman, G. D. (2009). Fixing a Critical Climate Accounting Error. *Science* **326**, 527–528.

Sebestyen, J. (2012). *Einfluss von räumlicher Heterogenität auf die Klimaeffekte von bioenergiegetriebenem Landnutzungswandel: Politikfolgenanalyse mittels agentenbasierter Modellierung*. Master's thesis, Universität Osnabrück.

Selic, B. (2003). The pragmatics of model-driven development. *Software, IEEE* **20**, 19–25.

Sen, A. (2008). Rational behaviour. In S. N. Durlauf and L. E. Blume, eds., *The New Palgrave Dictionary of Economics*. Basingstoke: Palgrave Macmillan.

Simon, C. and Etienne, M. (2010). A companion modelling approach applied to forest management planning. *Environmental modelling & software* **25**, 1371–1384.

Simon, H. (1957). *Models of Man*. John Wiley. New York.

Simon, H. A. (2008). Rationality, bounded. In S. N. Durlauf and L. E. Blume, eds., *The New Palgrave Dictionary of Economics*. Basingstoke: Palgrave Macmillan.

Sitch, S., Smith, B., Prentice, I. C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J. O., Levis, S., Lucht, W., Sykes, M. T., Thonicke, K. and Venevsky, S. (2003). Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology* **9**, 161–185.

Smajgl, A. and Bohensky, E. (2013). Behaviour and space in agent-based modelling: Poverty patterns in East Kalimantan, Indonesia. *Environmental Modelling & Software* **45**, 8 – 14.

Smajgl, A., Brown, D. G., Valbuena, D. and Huigen, M. G. A. (2011). Empirical characterisation of agent behaviours in socio-ecological systems. *Environmental Modelling & Software* **26**, 837–844.

Smed, J. and Hakonen, H. (2006). *Algorithms and networking for computer games.* Wiley Online Library.

Smeets, E., Weterings, R. and voor Toegepast-Natuurwetenschappelijk, N. C. O. (1999). *Environmental indicators: Typology and overview.* European Environment Agency Copenhagen.

Smith, K. A. and Searchinger, T. D. (2012). Crop-based biofuels and associated environmental concerns. *Global Change Biology Bioenergy* **4**, 479–484.

Smith, P., Haberl, H., Popp, A., Erb, K.-h., Lauk, C., Harper, R., Tubiello, F. N., de Siqueira Pinto, A., Jafari, M., Sohi, S., Masera, O., Böttcher, H., Berndes, G., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E. A., Mbow, C., Ravindranath, N. H., Rice, C. W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Herrero, M., House, J. I. and Rose, S. (2013). How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? *Global Change Biology* **19**, 2285–2302.

Sorda, G., Banse, M. and Kemfert, C. (2010). An overview of biofuel policies across the world. *Energy Policy* **38**, 6977–6988.

Sterner, M. and Fritsche, U. (2011). Greenhouse gas balances and mitigation costs of 70 modern Germany-focused and 4 traditional biomass pathways including land-use change effects. *Biomass & Bioenergy* **35**, 4797–4814.

Stoms, D. M., Davis, F. W., Jenner, M. W., Nogeire, T. M. and Kaffka, S. R. (2012). Modeling wildlife and other trade-offs with biofuel crop production. *Global Change Biology Bioenergy* **4**, 330–341.

Sukhdev, P., Wittmer, H., Schröter-Schlaak, C., Nesshöver, C., Bishop, J., ten Brink, P., Gundimeda, H., Kumar, P., Simmons, B. and Neuville, A. (2010). *The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature.* TEEB.

Sun, Z. and Müller, D. (2013). A framework for modeling payments for ecosystem services with agent-based models, Bayesian belief networks and opinion dynamics models. *Environmental Modelling & Software* **45**, 15 – 28.

Taillandier, P., Vo, D.-A., Amouroux, E. and Drogoul, A. (2012). GAMA: a simulation platform that integrates geographical information data, agent-based modeling and multi-scale control. In *Principles and Practice of Multi-Agent Systems*. Springer, pages 242–258.

Taubert, F., Frank, K. and Huth, A. (2012). A review of grassland models in the biofuel context. *Ecological Modelling* **245**, 84 – 93.

Tesfatsion, L. (2003). Agent-based computational economics: modeling economies as complex adaptive systems. *Information Sciences* **149**, 263–269.

Tesfatsion, L. (2006). Agent-based computational economics: A constructive approach to economic theory. In L. Tesfatsion and K. Judd, eds., *Agent-based Computational Economics*, volume 2 of *Handbook of Computational Economics*. North Holland, Oxford, pages 831 – 880.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C. and Williams, R. (2009). Beneficial biofuels—the food, energy, and environment trilemma. *Science* **325**, 270–271.

Tisue, S. and Wilensky, U. (2004). Netlogo: A simple environment for modeling complexity. In *International Conference on Complex Systems*.

Turner, B. L., Lambin, E. F. and Reenberg, A. (2007). The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences* **104**, 20666–20671.

Turner, M. G., Arthaud, G. J., Engstrom, R. T., Hejl, S. J. and Liu, J. (1995). Usefulness of spatially explicit population models in land management. *Ecological Applications* **5**, 12–16.

UNFCCC (2005). `unfccc.int/methods/redd/methodological_guidance/items/4123.php`. Accessed 01.09.2013.

UNFCCC (2013). `http://unfccc.int/kyoto_protocol/items/2830.php`. Accessed 28. August 2013.

Van den Bergh, J., Carbonell, A. and Munda, G. (2000). Alternative models of individual behaviour and implications for environmental policy. *Ecological Economics* **32**, 43–61.

van Oel, P. R., Krol, M. S., Hoekstra, A. Y. and Taddei, R. R. (2010). Feedback mechanisms between water availability and water use in a semi-arid river basin: A spatially explicit multi-agent simulation approach. *Environmental Modelling & Software* **25**, 433–443.

Voigt, S. (2009). *Institutionenökonomik*, chapter Einfache Transaktionen. UTB, pages 53–76.

Watts, C. and Gilbert, N. (2011). Does cumulative advantage affect collective learning in science? An agent-based simulation. *Scientometrics* **89**, 437–463.

WBGU (2009). *Welt im Wandel - Zukunftsfähige Bioenergie und nachhaltige Landnutzung*. WBGU.

Wilensky, U. and Rand, W. (2007). Making models match: Replicating an agent-based model. *Journal of Artificial Societies and Social Simulation* **10**, online.

Witcover, J., Yeh, S. and Sperling, D. (2013). Policy options to address global land use change from biofuels. *Energy Policy* **56**, 63–74.

Young, O. R., Lambin, E. F., Alcock, F., Haberl, H., Karlsson, S. I., McConnell, W. J., Myint, T., Pahl-Wostl, C., Polsky, C., Ramakrishnan, P. et al. (2006). A portfolio approach to analyzing complex human-environment interactions: institutions and land change. *Ecology and Society* **11**, 31.

Zeide, B. (1993). Analyis of growth equations. *Forest Science* **39**, 594–616.

Zhang, B., Zhang, Y. and Bi, J. (2011). An adaptive agent-based modeling approach for analyzing the influence of transaction costs on emissions trading markets. *Environmental Modelling & Software* **26**, 482–491.

Acknowledgements

First, I want to thank my supervisor Prof. Karin Frank for sharing her energy and her enthusiasm with me. Her ideas and her support where crucial factors for the growth of this thesis. I really appreciate that she, despite her huge work load, always found time to untangle confusion or to suggest ways out of a dead end. I also want to thank my co-supervisor Prof. Erik Gawel for his input. I am thankful for his ability to explain environmental economy in a clear and concise way and to put complex issues in a nutshell (which is an extremely useful foundation for modeling). In addition I want to thank Dr. Martin Drechsler and Dr. Karin Johst for their valuable comments and ideas during the phase of model conceptualization.

Henning Nolzen, Jule Schulze and Birgit Müller improved this thesis by reading and commenting parts of it. Furthermore, I want to thank two “crews” that have contributed with their ideas and comments during the ongoing PhD-project. These are the Journal Club for Agent-based Modeling of Land Use Decisions (consisting of Birgit Müller, Jürgen Groeneveld, Nina Schwarz, Carsten Buchmann, Friedrich Bohn, Gunnar Dreßler, Christian Klassert, Romina Martin, Henning Nolzen and Jule Schulze) and the working group Bioenergy International (consisting of Karin Frank, Erik Gawel, Christoph Görg, Grit Ludwig, Linda Bausch, Henning Nolzen, Christian Klassert, Alexandra Purkus and Vanessa Richarz).

In addition, I would like to thank the Oesians for making the OESA (Department of Ecological Modelling at the UFZ) an inspiring, international and friendly working place. I appreciate the numerous good discussions on life, the universe and everything with Claudia, Felix, Flo, Franzi, Guy, Jeroen, Joachim, Marcus, all those who are named Martin, Olli, Rico, Romina, Sandro and Thomas. My (ex-, and future) office-mates Alex, Friedrich and Henning contributed to this thesis by keeping me sane through chocolate, laughter and off-topic discussions. However, they also always had an open ear to discuss the PhD project and often helped with good comments and suggestions - thank you for that. The OESA IT, administration and library are kept running reliably by Gabi, Heike, Andreas and Michael - thank you.

I want to thank the Helmholtz Centre for Environmental Research (UFZ) for financing this thesis with a PhD position. I am also grateful for the courses and training that were facilitated by the Helmholtz Interdisciplinary Graduate School for Environmental Research (HIGRADE).

I am very grateful to the people who make me feel at home in Leipzig, as well as companions with whom I have travelled the most interesting roads: thanks Anke, Astrid, Kay, Levke, Monika, Nicole, Nina, Peggy and Wibke. Thank you very much C. for tolerating the homogeneous grid-cells and their virtual owners that absorbed quite a bit of my time and my energy. Thank you even more for luring me away from them when necessary and sharing a neither homogeneous nor fully informed or perfectly rational but colorful life with me. Last but not least I want to thank my brother, my parents and my grand-parents for their continuous support and encouragement.