Quantifying relationships between governance, agriculture, and nature: empirical-statistical- and pattern-oriented modeling

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General introduction

1.1. Ways of including governance into land-use modeling

1.1.1. *Scientific and societal relevance*

Land use is characterized by arrangements, activities, and inputs by humans to produce, change, or maintain particular land-cover types (Di Gregorio and Jansen, 1998), establishing a direct interface between human behavior and observed land cover. Consequently, land use is generally the outcome of a complex process of interfacing biophysical, geographical, and socio-economic determinants (Kok and Veldkamp, 2001). It has therefore been recognized that multi-disciplinary research is crucial for the progress in land-use science (Veldkamp and Verburg, 2004), and that integration of social- and natural-science approaches is required to achieve improved understanding of how land use impacts on the ecosystems in which it is embedded (Veldkamp and Lambin, 2001; Brown et al., 2013). Owing to their quantitative nature, economic models (general- and partial equilibrium models in particular) have long since been integrated with land-use models (Irwin and Geoghegan, 2001), together with geographic information systems. However, a very important and extremely challenging component that is still largely missing from such integrated land-use models is how to model "Governance by governing" behavior (*1.1.2.1. Governance*, Table 1) that occurs not only for economic reasons but also for other governance-related reasons (Irwin and Geoghegan, 2001). An improved understanding of how complex processes of both socio-political and "Economic governance" (*1.1.2.1. Governance*, Table 1) shape land-use patterns would represent a crucial step forward. It could allow, for example, for land-use policies that are better suited to the high complexity common to governing behavior encountered across various levels of geographical spatial scale. Furthermore, given the increasing pressures of rising global food demand and agricultural land use on nature (Lambin et al., 2000; Verburg et al., 2013), an improved understanding of this complexity is desirable, so that further negative effects of these increasing pressures can be minimized. However, this requires further disciplinary integration of—and therefore reconciliation of fundamental differences between—social and natural science perspectives of governance and land use, respectively. In the social sciences, predominantly social-constructivist perspectives of governance have been adopted for meaningful interpretations of observed governing behavior (*1.1.2.1. Governance*, Table 1), consistent with viewing society as an abstract whole in which individuals create governance networks- and knowledge through social interactions.

1.1.2. *Background*

1.1.2.1. *Governance*

Despite the clear added value of qualitative perspectives of governance (Table 1), such perspectives are only little concrete and do not provide any handholds for quantitative analysis. That is, the adoption of a more social-positivistic perspective of governance is unavoidable if we wish to integrate social-science based concepts of governance with quantitative natural-science based concepts of land use. Although hardly any social-positivistic concepts of governance have been developed due to its qualitative nature, the field of adaptive governance (Table 1, "Adaptive governance") does have the ambitious goal of developing new concepts of governance that can handle the inherent complexity and unpredictability of dynamic social-ecological systems through self-organization and adaptation. Furthermore, the more modern descriptions of governance in Table 1 have been developed largely as a critique of state-centric governance, also referred to as hierarchical governance (Hill and Lynn, 2004), the government perspective (Rhodes, 1997), command and control systems of governance (Kooiman, 1993), or the classical-modernist approach of governance (Hajer and Wagenaar, 2003). Hitherto, however, the traditional provision of information to policymakers by science remains the foremost factor at the basis of real-world governance.

Furthermore, as the research in this thesis is concerned with real-world effects of governance on land use it would not benefit from an attempt at integrating quantitative process-based relationships into social-constructivist perspectives of governance. Although land use is also studied from more qualitative perspectives, e.g., in the fields of land-use policy- or planning, or landscape architecture, quantitative studies usually do have a greater scientific impact. This derives from the importance of future projections and predictions of land use to integrated impact assessments regarding e.g., climate change, soil degradation, or loss of biodiversity. That is, these projections and predictions may only be obtained through quantitative studies (e.g., simulation models, scenario analyses, or empirical-statistical analyses). Moreover, real-world governance of land results from policy designs that are directly or indirectly based on empirical numeric data (e.g., from such integrated impact assessments) that provide quantitative and verifiable evidence for concrete relationships, or critical conditions or thresholds relevant to specific phenomena.

Therefore, objective and quantitative indicators of governance should be integrated into quantitative empirical-statistical- and process-based modeling approaches that attempt to explain how land-use patterns come to exist. This way, it might be possible to assess impacts of complex decision-making processes on land-use patterns using numeric data of quantified social-science concepts (both at an aggregate level and at the individual level), which might in turn allow for better real-world governance of such impacts across various levels of geographical spatial scale (Cash et al., 2006).

Table 1. Different qualitative perspectives of governance.

State-centric governance	State-centric governance refers to the traditional viewpoint in which the state is the center of political power and authority (Rhodes, 1997; Pierre, 2000; Kooiman, 2003). The state exerts control over society, economy, and resources by setting the agenda of societal problems, deciding upon which policy goals and means to follow, and by top-down implementation of policies.
Good governance	The earliest noteworthy form of ‘modern’ governance was in the field of economic development, where the World Bank and other international organizations emphasized the need for ‘sound’ or ‘good governance’. Stressing the political, administrative, and economic values of legitimacy and efficiency (Rhodes, 2000; Kaufmann et al., 2009), this entails reducing public spending; investing in health, education, and social security; promoting private sectors by regulatory reform; reinforcing private banking; tax reforms; and greater transparency and accountability in government-corporate relationships (Kiely, 1998; Philip, 1999; Rosenbaum and Shepherd, 2000; Woods, 2000).
Economic governance	Economic governance is concerned with markets and their governing institutions. In this approach, the fields of new institutional economics (Williamson, 1975, 1985, 1996), economic sociology (Smelser and Swedberg, 1994), and comparative political economy (Hollingsworth and Boyer, 1997; Crouch and Streeck, 1997; Hall, 1999) have been brought together by emphasizing that markets are not spontaneous social orders, but have to be created and maintained by institutions. These provide, monitor, and enforce rules which among other things regulate property rights, contracts, competition, and reduce risk, asymmetry of information, and uncertainty.
Governing without government	The possibility of governing without government stems from international relations theory (Rosenau and Czempiel, 1992). Traditionally, international relations are seen to be characterized by competing and interdependent states that acknowledge no other authority than their own (Lieshout, 1995). However, international politics are decreasingly seen as solely being a cooperation between independent states. Rather, they are increasingly seen as new forms of international governance that sustain mechanisms designed to ensure coherence, stability, and safety (Rosenau, 2000). These mechanisms, traditionally found in governments, are increasingly found in international organizations, treaties, and regimes.

Adaptive governance	Adaptive governance refers to the self-organizational capacity of societies and communities. Pioneering work in this field was done by Ostrom (1990), studying the capacity of communities in different places and times to manage common-pool resources and prevent their depletion. Adaptive governance evolved from the original development of adaptive management of ecological systems, after having been put forward as an integrated, multidisciplinary approach for confronting complexity and uncertainty in natural-resource issues (Holling, 1978; Berkes and Folke, 1998; Gunderson, 1999; Folke et al., 2005).
Multi-level governance	Multi-level governance has two distinct origins. It is seen as a modernization of the earlier regime concept in international relations theory (Hasenclever et al., 1997). Governance is strongly related to this concept: it refers to the substance of policies as well as to the power relations resulting from such policies (Krasner, 1983). 'Multi-level' refers to different government levels (e.g., European, national, subnational), but also to public and private actors involved at these levels. The other origin of multi-level governance can be found in the field of comparative public policy analysis of Europe (Rhodes and Mazey, 1995; Hurrel and Menon, 1996; Richardson, 1996; Bulmer, 1998; Peterson and Bomberg, 1999). Furthermore, it is acknowledged that the importance of policy networks organized across different levels of government cannot be denied (Marks et al., 1996). Therefore, multi-level governance literature is deeply connected to governance-network literature in general (Héritier, 1999).
Governance by governing	Governance by governing is derived from the fact that "governing" encompasses all activities of social, political, and administrative actors that can be seen as purposeful efforts to guide, steer, control, or manage the pursuance and realization of public goods, and collective or individual goals (Kooiman, 1993; Kjaer, 2004). Based on this, Termeer et al. (2010) defined governance as all modes of governing, regardless of whether they were developed and enforced by markets (economic governance), hierarchies (government), or networks (multi-level governance).

1.1.2.2. *Empirical-statistical- and process-based modeling*

There are two possible approaches to the modeling of real-world governance in the context of land-use modeling: empirical-statistical (rule-based) modeling and process-based modeling. What separates these types of models from social-constructivist perspectives of governance is that they would allow for verifiable inferences whereas the latter do not. That is, the latter approach would take the importance of governance in land-use change processes as a starting point, whereas the former approach would frame this as a research question to be answered by empirical means. On the one hand, the more empirically specific the way in which research questions are formulated, the easier it is to answer them. Case studies for which numeric data can be obtained allow for specific and verifiable inferences. However, the degree of generality of such inferences is limited to the confines of study areas, valid only under study-specific conditions. On the other hand, the more general and abstract the way in which research questions are formulated, the more difficult it is to answer them. However, the more general the conditions (e.g., spatial extent, behavioral assumptions) under which research questions can be answered the better. This means that a tradeoff has to be made between the degree of generality (abstraction) and empirical specificity (allowing for validation of such abstraction) to achieve a maximum degree of verifiable generality, both in empirical-statistical- and process-based modeling.

1.1.2.2.1. Empirical-statistical modeling

For empirical-statistical models, the higher the level of aggregation and thus the level of abstraction, the more open to interpretation found relationships would be (due to lower empirical specificity). That is, the higher the level of abstraction, the more difficult it becomes to link statistical relationships to real-world processes, as the number and complexity of spatiotemporal processes that could explain them grow beyond our ability to disentangle and comprehend. Such processes may also occur across different levels of spatiotemporal scales, further complicating meaningful analysis. Conversely, the higher the empirical specificity, the more geographically restricted the validity of inferences would be. However, found statistical relationships would then also be more concrete and more likely to pertain to clearly identifiable key processes. Furthermore, an empirical-statistical governance model would require quantification of socially constructed perceptions of governance to make statistical inferences, and it would not be based on positivistic general behavioral laws (as would be the case for a process-based model). That is, quantitative results from an empirical-statistical governance model would still have to be interpreted in the context of a social-constructivist perspective of governance (Table 1). Therefore, in this thesis, the empirical-statistical approach to the modeling of governance is thought of as semi-positivistic, which could possibly be used to perform empirical analyses of how agricultural land use and nature relate to quantified perceptions of “State-centric governance” (Table 1).

As mentioned, to allow for statistical inferences made with an empirical-statistical model of governance, quantification of socially constructed perceptions of governance is required. Recently, the World Bank has formed a research dataset summarizing quantified perceptions of state-centric governance (Table 2), provided by a large number of enterprises, citizens, and expert survey respondents in industrial and developing countries (World Bank, 2014b). These data were gathered by the World Bank from a number of survey institutes, think tanks, non-governmental- and international organizations, and private-sector firms (totaling 30 sources). Each dimension of governance was constructed by averaging data from the underlying sources corresponding to the perception of governance being measured

(World Bank, 2014a). The resulting estimates are weighted averages of the data from each source, with weights reflecting the pattern of correlation among data sources, for each dimension of governance. While this weighting improves the statistical precision, the estimates for each dimension of governance are in units of a standard normal distribution with mean zero and standard deviation of one, running from approximately-2.5 to 2.5, higher values corresponding to higher scores of quality of governance.

Table 2. The World Bank dimensions of governance.

Dimension	Definition
Voice and accountability	Measures the public perception of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.
Government effectiveness	Measures the public perception of the quality of public- and civil services, the degree of independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.
Regulatory quality	Measures the public perception of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.
Rule of law	Measures the public perception of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.
Control of corruption	Measures the public perception of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.
Political stability and the absence of violence	Measures the public perception of the likelihood of destabilization or overthrowing of a government by unconstitutional or violent means, leading to domestic violence and terrorism.

Source: World Bank, http://info.worldbank.org/governance/wgi/index.aspx#home.

These World Bank dimensions of governance in Table 2 can be used as indicators in a semi-positivistic approach to studies of how quantified perceptions of state-centric governance relate to agricultural expansion and/or intensification and dominant spatiotemporal processes of fragmentation of nature. More specifically, such a semi-positivistic approach could be used to study whether—and if so, how—state-centric governance directly drives expansion and/or intensification of arable agriculture, in response to the rising global food demand (*1.2.1.1. Research question 1*). Furthermore, such a semi-positivistic approach could be used to study whether—and if so, how—state-centric governance directly drives dominant spatiotemporal processes of fragmentation of nature (*1.2.1.2. Research question 2*). In turn, results might be used to study whether—and if so, how—such processes of fragmentation of nature are also indirectly driven by state-centric governance (*1.2.1.3. Research question 3*), through the processes of expansion and/or intensification of arable agriculture. Together, this could allow for a comprehensive overview of how these land-use change processes are—directly and indirectly—driven by state-centric governance at supranational level, and how they interact.

1.1.2.2.2. Process-based modeling

A process-based governance model would require general behavioral laws rather than quantification of socially constructed perceptions of governance (as would be the case for an empirical-statistical model). Therefore, in this thesis, the process-based approach to the modeling of governance is thought of as positivistic, which could possibly be used to perform empirical analyses of how patterns of agricultural land use and nature relate to general laws of governance. Similar to the empirical-statistical approach, the number and complexity of spatiotemporal processes that could explain observed land-use patterns, grow with the extent of the study area on which a process-based model would be applied (i.e., for validation). That is, even when simulated land-use patterns are similar to observed patterns, other key processes involved that could not be included into the model due to their complexity may also have been responsible for observed land-use patterns. Furthermore, the higher the degree of abstraction with which processes are modeled the lower their empirical specificity. That is, the more general and abstract relationships that are assumed to regulate processes are, the less easily they can be expressed in measurable quantities (which may ultimately result in an oversimplified model). Conversely, the more empirically specific and based on measurable quantities such general relationships are, the more difficult it becomes to describe how all these quantities interact in a consistent way (which may ultimately result in an overly complex model).

Quantifying generalized verifiable relationships between individual decision-making (i.e., local governance) and aggregate land-use patterns is one of the major challenges for the next generation of land-use models (Irwin and Geoghegan, 2001; Parker et al., 2008a). It is believed that Pattern-Oriented Modeling (POM), which attempts to reproduce real-world aggregate patterns with those that emerge from individual decision-making processes (Grimm et al., 2005, 2006; Piou et al., 2009), holds the potential to a better understanding of land-use systems that are too complex to be understood by empirical analysis alone (Grimm et al., 2005; Evans and Manson, 2007; Liu et al., 2007; Wiegand et al., 2008). Furthermore, increasingly successful attempts have been made to view land-use systems as dynamic social-ecological systems, from the perspective of individual-based modeling (Parker et al. 2003; Jepsen et al., 2006; Brown et al., 2008; Lopez-Carr et al., 2011). Therefore, it may be possible to construct a pattern-oriented land-use model of agriculture and nature, based on individual decision-making processes regulated by general laws of local and aggregate governance, with which relationships between emergent land-use patterns and differences in local and/or aggregate governance could be empirically investigated (*2.2.1. Research question 4*). That is, determining which combination of modeled biophysical- and governance processes approximates real-world patterns best, with a classical positivistic approach of iterating cycles of theory and observation.

1.2. Research questions

1.2.1. ***Empirical-statistical modeling***

1.2.1.1. *Research question 1*

Does state-centric governance directly drive—and if so, how—expansion and/or intensification of arable agriculture?

1.2.1.2. *Research question 2*

Does state-centric governance directly drive—and if so, how—dominant spatiotemporal processes of fragmentation of nature?

1.2.1.3. *Research question 3*

If state-centric governance drives expansion and/or intensification of arable agriculture directly, does it also drive—and if so, how—processes of fragmentation of nature through these processes?

1.2.2. ***Process-based modeling***

1.2.2.1. *Research question 4*

Is it possible—and if so, how—to systematically and verifiably approximate real-world dynamic complexity of agricultural land-use systems and their governance with a pattern-oriented modeling approach based on individual decision-making processes?

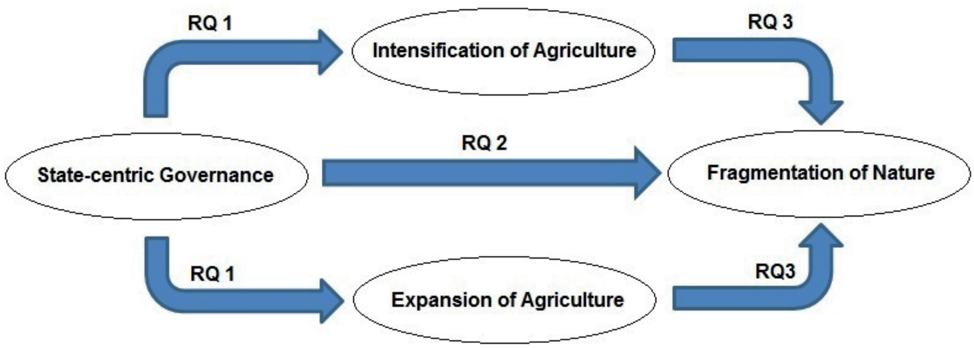

Fig. 1. Schematic illustration of empirical-statistical research questions (RQs).

1.3. Structure guide

In chapters 2 and 3 of this thesis it is investigated whether state-centric governance directly drives—and if so, how—expansion and/or intensification of arable agriculture (*1.2.1.1. Research question 1*), and whether state-centric governance directly drives—and if so, how—dominant spatiotemporal processes of fragmentation of nature (*1.2.1.2. Research question 2*), respectively. Furthermore, in chapter 4 it is investigated whether it is possible—and if so, how—to systematically and verifiably approximate real-world dynamic complexity of agricultural land-use systems and their governance with a pattern-oriented modeling approach based on individual decision-making processes (*1.2.2.1. Research question 4*). While in chapter 5, an attempt is made at simulating the interplay between governance, agricultural land use, and nature, identified through empirical-statistical means (*1.2.1. Empirical-statistical modeling*) with a constructed process-based simulation model (*1.2.2. Process-based modeling*). In chapter 6 it is discussed whether—and if so, to what extent—the research questions posed in this thesis could be answered by applying these empirical-statistical- and process-based modeling approaches. In addition, the value added by viewing separate research findings together is discussed in this chapter, and how these different approaches dealt with the real-world complexity of chosen land-use change processes.

Deconstructed I have been,
A phoenix of sadness,
Reborn and reconstructed,
From the ashes of madness.

2

The role of governance in agricultural expansion and intensification: A global study of arable agriculture

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Abstract

In this research we studied empirical relationships between agricultural production dynamics and six quantitative World Bank governance indicators for 173 countries between 1975 and 2007. It is hypothesized that in countries with lower quality of governance, agricultural production increases are more likely to be achieved by area expansions than by increases in yields. We distinguished four groups of countries: those with both area and yield increases; those with increasing yields but decreasing area; those with decreasing yields but a growing area; and those with both declines in yields and area. We analyzed differences between these four groups, and also analyzed governance-production relationships within these groups. On average, quality of governance is low in countries with both area and yield increases and high in countries with increasing yields but decreasing area. Countries with declining yields were too few in number to allow for quantitative analyses. The analysis of governance-production relationships within the four groups suggests that countries with a lower quality of governance are more inclined to achieve production increases by expanding agricultural area rather than increasing yields. Additional explanatory value of governance indicators to agricultural production dynamics is generally small, but nevertheless significant in most cases. Our results suggest that, in order for agricultural production to increase without excessive expansions of agricultural area, governance issues should be resolved. Should we assume a causal relationship, the tendency of expanding cultivated area in less developed countries can be stopped by improving the quality of governance.

Keywords: development, intensification, governance, cropland, farming, empirical.

2.1. Introduction

Recently, the Food and Agriculture Organization of the United Nations (FAO) adjusted its projections of future food and feed demand (FAO, 2009c). Because of population growth and, more importantly, a rise in economic welfare, global food and feed production should increase with 70 % by 2050. In order to attain such an increase in production, cultivated area has to expand and/or yields have to increase. Although some argue that there is a vast potential for yield increase to meet the required production increase (Neumann et al., 2010), the question remains whether or not this increase in yields is likely to happen. The potential for yield increase is highest in developing countries, where current productivity levels are far below potentially attainable levels (Marra et al., 2003; Byerlee and Fischer, 2002). However, many developing countries are also characterized by a lower quality of governance, which may hinder yield increase for a number of reasons. One is that investments in research and development are too low to achieve the (region-specific) technology required for yield increase; second is that the investment-climate at farm level is often unfavorable so that buying equipment and inputs required for intensification is difficult; and thirdly, natural areas are abundant and not well protected, making expansion of agricultural area at the expense of nature an attractive alternative to intensification (Kakonge, 1998).

In the past, many attempts have been made to describe and predict agricultural yields and land use at a global level. Most of the studies concerning yields had a biophysical character (Soltani et al., 1999; Harrison et al., 2000; Hafner et al., 2003; Nuemann et al., 2010), while most of the land use studies had an economic character (Veldkamp and Fresco, 1996; Rounsevell et al., 2005; Eickhout et al., 2006; Mittenzwei et al., 2007). Although numerous examples of cases where rural conditions were affected by governance can be found in literature, quantitative, global analyses of governance effects on agriculture are few. Those that sketch effects of policies are relatively abundant (EC, 2000; Van Kersbergen and Van Waarden, 2004; Biermann, 2007; Jansson et al., 2008), but those that relate overall governance quality to agriculture are rare. Only recently more attention has been paid to governance effects (IFPRI, 2006; IFPRI, 2008; FAO, 2009a, 2009b) on agriculture. These qualitative studies related governance regarding land transactions (access to market, property rights enforcement) to investments in research and development (yield increase). However, they did not demonstrate that governance characteristics are indeed significant factors for aggregate agricultural production. In general it can be said that governance studies were mostly characterized by qualitative studies of one single regime, which could hardly be used to make global quantitative inferences (Cash et al., 2006). Now that the World Bank made a global inventory of governance indicators, we can identify the role of governance in agricultural dynamics.

To examine whether or not governance characteristics are indeed significant factors determining production increases, and whether these are obtained from yield increase or from area expansion, an empirical analysis of historical tendencies of yield increase and area expansion was performed. These observed agricultural production dynamics (i.e., changes in cultivated arable area and crop yields) were related to six governance indicators that were recently produced by the World Bank (Kaufmann et al., 2009). Using linear regression techniques we test the hypothesis that in countries with lower quality of governance, agricultural production increase is more likely to be achieved by area expansion than by increase in yield.

Table 1. Production-, governance- and control indicators.

Indicators	Source
Production indicators	
Aggregate change in total agricultural production (-)	F.A.O. †
Aggregate change in total cultivated area (-)	F.A.O. †
Aggregate change in yield (-)	F.A.O. †
Governance indicators	
Voice and accountability (index between-2.5 and 2.5)	World Bank‡
Government effectiveness (index between-2.5 and 2.5)	World Bank‡
Regulatory quality (index between-2.5 and 2.5)	World Bank‡
Rule of law (index between-2.5 and 2.5)	World Bank‡
Political stability and absence of violence/terrorism (index between-2.5 and 2.5)	World Bank‡
Control of corruption (index between-2.5 and 2.5)	World Bank‡
Control indicators	
Change in agricultural export value index (-)	F.A.O. §
Initial agricultural export value index (share of total export value) (-)	F.A.O. §
Change in agricultural import value index (-)	F.A.O. §
Initial agricultural import value index (share of total import value) (-)	F.A.O. §
Change in net trade flow value (export minus import) (-)	F.A.O. §
Initial net trade flow value (export minus import) (share of total value) (-)	F.A.O. §
Change in GDP (PPP) (-)	World Bank|
Initial GDP (PPP) (International $/capita/yr)	World Bank|
Change in economically active agricultural population (-)	F.A.O. ¶
Initial economically active agricultural population (share of total) (-)	F.A.O. ¶

Change in total population (-)	F.A.O. ¶
Initial total population density (persons/Km2)	F.A.O. ¶
Change in total economically active population (-)	F.A.O. ¶
Initial economically active population (share of total) (-)	F.A.O. ¶
Change in urban population (-)	F.A.O. ¶
Initial urban population (share of total) (-)	F.A.O. ¶
Change in rural population (-)	F.A.O. ¶
Initial rural population (share of total) (-)	F.A.O. ¶
Annual mean temperature (°C)	Worldclim#
Annual precipitation (mm)	Worldclim#
Fraction of area constrained by aluminum toxicity (-)	F.A.O. ††
Fraction of area constrained by salinity (-)	F.A.O. ††
Fraction of area constrained by high phosphorus fixation (-)	F.A.O. ††

†F.A.O., faostat, 01-09-09 (http://faostat.fao.org/site/567/default.aspx#ancor); §F.A.O., tradestat, 01-09-09 (http://faostat.fao.org/site/406/default.aspx); ¶F.A.O., popstat, 01-09-09 (http://faostat.fao.org/site/452/default.aspx); ††F.A.O., terrastat, 01-09-09 (http://www.fao.org/ag/agl/agll/terrastat); ‡World Bank, 01-05-09 (http://info.worldbank.org/governance/wgi); |World Bank; World Development Indicators, 01-05-09 (http://www.worldbank.org/data); The international dollar is a hypothetical unit of currency that has the same purchasing power that the U.S. dollar had in the United States at a given point in time; in this case the year 2000; #Worldclim, 01-05-09 (http://www.worldclim.org/methods).

2.2. Data and methods

When studying real-world phenomena that are the result of complex processes by means of regression analysis, it is hardly ever possible to isolate the role of the explanatory variable of interest from a wide range of other explanatory variables. In our case, we are interested in how well governance indicators can explain agricultural production indicators, but we cannot escape from the fact that governance is correlated to many other variables that also explain production indicators (e.g., climate, soils, economy and demography). For this reason, we try to include these other variables as much as possible, to account for their potential impact. We will refer to these variables as control indicators. Because of statistical confounding we will not be able to distinguish exactly which part of the explanatory power of the regression can be attributed to each of the two categories (the governance indicators and the control indicators). We can nevertheless measure a range of the explanatory power of governance. The upper limit of this range is provided by the explanatory power of the governance indicators only, and the lower limit is provided by the explanatory power of the governance indicators in addition to the explanatory power of the control indicators. The upper limit is likely to overestimate explanatory power of governance, as this estimate assumes that all common explanatory power of the two categories of indicators should be attributed to the governance indicators only. Conversely, the latter one is likely to underestimate explanatory power of governance, as this estimate assumes that all common explanatory power of the two categories of indicators should be attributed to the control indicators. Therefore, true explanatory power of governance is likely to be within this range (Bakker et al., 2005).

2.2.1. *Data*

Because all indicators had to be measured in a similar manner for all countries in the analysis, we were limited to use global databases such as those of the FAO and the World Bank. Countries for which no (consistent) data existed because they either merged or split up into separate states during the study period (1975–2007), e.g., former USSR, former SFRY, Czech Republic, Slovakia and Ethiopia, were not included. In total, 173 countries were included in the analysis. As we are interested in dynamics, most indicators were computed as relative changes between (approximately) 1975 and 2007. Only for those indicators that were considered static in time (e.g., soil variables) or for which sufficiently long time series were not available (governance), a state variable was used. For most of the control indicators, both a change and a (initial) state value were used. Changes were computed as the ratio between initial states and final states. In order to correct for inter-annual variability, initial states were computed as the average over the period 1975–1980 and final states were computed as the average over 2002–2007. All dependence on country size and population size was eliminated by working with relative values (e.g., changes relative to the initial value or densities or fractions).

2.2.1.1. *Production indicators*

Production dynamics between 1975 and 2007 were expressed in terms of change in production, change in yield, and change in cultivated area, all between 1975 and 2007 (Table 1). Clearly, one of these three indicators is superfluous, i.e., given any two of these, the third can be calculated. For this reason, we only use changes in yield and cultivated area. However, the mathematical relationship that describes how these latter two indicators contribute to production change provides insight that is important for interpretation. Therefore, production change is also described in the derivation below, although it is not used in the analyses.

Yield changes were calculated for all different crop types recorded in the FAO database[1], after which a weighted average was calculated on the basis of the average cultivated area per crop type:

$$dY \equiv Log\left[\frac{\sum_i \left(\frac{A_i Y_{1i}}{Y_{0i}}\right)}{\sum_i A_i}\right] \approx Log\left[\frac{Y_1}{Y_0}\right] \tag{1}$$

In order to account for inter-annual yield variability, $Y_{1,i}$ is the average yield over 2002–2007, for crop *i*, and $Y_{0,i}$ is the average yield over 1975–1980, for crop *i*. A_i is the average cultivated area for crop *i* over 1975–2007. By computing yield changes separately for all individual crops before averaging, effects of shifts from heavy crops (e.g., potatoes) to light crops (e.g., fibers), or from crops undergoing strong yield increase to crops undergoing small yield increase, are not mistaken for yield changes. All changes were expressed as the log of the ratios of these averaged initial and final values, in order to rescale the skewed distribution and non-equidistant data, resulting from working with positive ratios and strongly varying growths/declines. This expression (Eq. 1) is defined as *dY* and approximates the yield change at national level (Y_1 divided by Y_0).

Similarly, changes in cultivated area were also calculated for all of the recorded crop types:

$$dA \equiv Log\left[\frac{\sum_i A_{1i}}{\sum_i A_{0i}}\right] = Log\left[\frac{A_1}{A_0}\right] \tag{2}$$

in which $A_{1,i}$ is the average cultivated area over 2002–2007, for crop *i*, and $A_{0,i}$ is the average cultivated area over 1975–1980, for crop *i*. This expression is defined as *dA* and approximates the change in total cultivated area at national level (A_1 divided by A_0).
By calculating change in this way, one creates dimensionless quantities providing information on change between the first and last five years, standardized for country-dependent

[1] Agave Fibres Nes, "Almonds, with shell", "Anise, badian, fennel, corian.", Apples, Apricots, Arecanuts, Artichokes, Asparagus, Avocados, Bambara beans, Bananas, Barley, "Beans, dry", "Beans, green", Berries Nes, Blueberries, "Broad beans, horse beans, dry", Cabbages and other brassicas, Carobs, Carrots and turnips, "Cashew nuts, with shell", Cashewapple, Cassava, Castor oil seed, Cauliflowers and broccoli, Cherries, Chestnuts, Chick peas, Chicory roots, "Chillies and peppers, dry", "Chillies and peppers, green", Cinnamon (canella), "Citrus fruit, nes", Cloves, Cocoa beans, Coconuts, "Coffee, green", "Cow peas, dry", Cranberries, Cucumbers and gherkins, Currants, Dates, Eggplants (aubergines), Fibre Crops Nes, Figs, Flax fibre and tow, Fruit Fresh Nes, "Fruit, tropical fresh nes", Garlic, Ginger, Gooseberries, Grapefruit (inc. pomelos), Grapes, "Groundnuts, with shell", "Hazelnuts, with shell", Hemp Tow Waste, Hempseed, Hops, Jute, Kapok Fibre, Kapokseed in Shell, Karite Nuts (Sheanuts), Kiwi fruit, Kolanuts, "Leguminous vegetables, nes", Lemons and limes, Lentils, Lettuce and chicory, Linseed, Lupins, Maize, "Mangoes, mangosteens, guavas", Manila Fibre (Abaca), Maté, Melonseed, Millet, Mushrooms and truffles, Mustard seed, Natural rubber, "Nutmeg, mace and cardamoms", "Nuts, nes", Oats, Oil palm fruit, "Oilseeds, Nes", Okra, Olives, "Onions (inc. shallots), green", "Onions, dry", Oranges, Other Bastfibres, Other melons (inc.cantaloupes), Papayas, Peaches and nectarines, Pears, "Peas, dry", "Peas, green", Pepper (Piper spp.), Peppermint, Persimmons, Pigeon peas, Pineapples, Pistachios, Plantains, Plums and sloes, Poppy seed, Potatoes, "Pulses, nes", "Pumpkins, squash and gourds", "Pyrethrum, Dried", Quinces, Quinoa, Ramie, Rapeseed, Raspberries, Rice Paddy, Rye, Safflower seed, Seed cotton, Sesame seed, Sisal, Sorghum, Sour cherries, Soybeans, "Spices, nes", Spinach, "Stone fruit, nes", Strawberries, String beans, Sugar beet, Sugar cane, "Sugar crops, nes", Sunflower seed, Sweet potatoes, "Tangerines, mandarins, clem.", Taro (cocoyam), Tea, "Tobacco, unmanufactured", Tomatoes, Triticale, Tung Nuts, Vanilla, Vegetables fresh nes, Vetches, "Walnuts, with shell", Watermelons, Wheat, Yams, Yautia (cocoyam)

properties such as size. Adding the left and right hand sides of Eq. 1 and Eq. 2, we obtain an approximation of the change in total production at national level, defined as *dP*:

$$dY + dA = Log\left[\frac{Y_1}{Y_0}\right] + Log\left[\frac{A_1}{A_0}\right] \approx Log\left[\frac{P_1}{P_0}\right] \equiv dP \tag{3}$$

Therefore, dY can be interpreted as the relative contribution of a change in yield to dP, thus reflecting a trend towards more intensive ($dY > 0$) or towards less intensive ($dY < 0$) agriculture. Similarly, dA can be interpreted as the relative contribution of a change in cultivated area to dP, thus reflecting a trend towards more extensive ($dA > 0$) or towards less extensive ($dA < 0$) agriculture.

2.2.1.2. *Governance indicators*

The World Bank identified six indicators for governance (Kaufmann et al., 2009):

Voice and Accountability represents the extent to which citizens have political rights and civil liberties, and are able to participate in selecting their government. Yields were found to be significantly higher in countries with more political rights and civil liberties (Fulginiti et al., 2004), indicating that agricultural development is related to “voice and accountability”. Agricultural development requires interactions between the rural population (e.g., labor unions and agricultural associations) and government agencies (e.g., extension service and ministry of agriculture). Such interactions are believed to benefit from political rights and civil liberties. Furthermore, governance influences agricultural policies, tax levels, and the conditions under which subsidies are granted. The extent to which the (rural) population can influence governance (by political votes) is therefore supposed to express itself in improved conditions for the rural population (Binswanger and Deininger, 1997).

Government Effectiveness refers to the provision, by government agencies, of public goods and services (and quality thereof), such as infrastructure and governmental agricultural research programs. Infrastructure plays a key role for the agricultural potential of remote rural areas to be used; agricultural research & development play a key role for yield increases (Thirtle et al., 2003). Therefore, whether or not these public goods and services can be delivered effectively by the government, is crucial to agricultural development. Moreover, “government effectiveness” is known to provide an adequate measure with respect to the quality of these public goods and services, and in particular for agricultural research and development (Thirtle and Piesse, 2007).

Regulatory Quality expresses how well private sector development is promoted by the government. A poor promotion of private sector development may negatively affect the performance of free-market mechanisms and investment climate (e.g., making it difficult for investors to get loans). In many countries, poor regulatory quality is caused by industrial protectionism: domestic trade policies disturbing the balance between domestic and world prices and preventing access to international markets, thereby obstructing private sector development (Lio and Liu, 2008). Furthermore, countries with poor regulatory quality tend to implement policies that result in high taxation of agriculture, which also has negative effects on private sector development and investment (Krueger et al., 1991).

Rule of Law represents quality of contract- and law enforcement in general. Poor contract- and law enforcement hinders the protection of property, and rights of landowners and tenants. In that case, advances in agricultural development (yield increase) are unlikely, as these advances strongly depend on private investments in agricultural research and development (Thirtle et al., 2003). Such investments are not likely to be made when investors cannot be assured of future revenues.

Political Stability and Absence of Violence measures the public perception of the likelihood of destabilization or overthrowing of a government by unconstitutional or violent means, leading to domestic violence and terrorism. It is well known that when violent political conflicts arise in a country, food security is compromised by failure of economic and social networks (Hussain and Herens, 1997). In countries facing higher levels of political conflict and war, yields were reported to be significantly lower during these periods (Fulginiti et al., 2004). Therefore, violent political destabilization or overthrowing of government would have negative effects on agriculture.

Control of Corruption refers to the extent to which public power is abused for private goals and gain. In countries where corruption is controlled, impartial authorities are often provided to check for corruption of conventional authorities and to hold them accountable if necessary. This increases the likelihood that power and funds are used for what they were intended. In countries that fail to control corruption, powerful individuals have the opportunity to abuse their influence to their advantage, at the expense of other less powerful individuals (e.g., farmers). For example, it has been suggested that large fertilizer producers persuaded African governments to impose particular fertilization programs upon farmers through bribery and other forms of corruption (World Bank, 2010), despite the fact that farmers often knew more about the particular deficits of their soils. Imposing these programs resulted in a loss of this knowledge, while crop yields hardly benefited from the traditional N, P and K fertilizers that were, after all, developed in and for temperate zones.

Annual governance indicator data were available for all six indicators and all 173 countries, during 1996–2008. This period is too short to compute a meaningful relative change, and does not correspond to the period for which other indicators were available (1975–2007). Therefore, averages were calculated over 1996–2008 for all governance indicators, which were included in the regression.

2.2.1.3. *Control indicators*

Control indicators include biophysical, demographic, and economic indicators (Table 1). These control indicators were chosen because they are known to be important determinants of agriculture in general. Most control variables are correlated with governance for a variety of reasons. As mentioned earlier, because of this correlation we can only identify a range of likely governance impact. Because we also include control indicators that are quite closely connected to governance (particularly the economic indicators), we limit our assessment of governance importance to that aspect of governance that is independent from economic performance. As economic indicators are generally associated with overall quality of governance, the marginal explanatory values of governance are likely to be underestimations.

2.2.2. *Methods*

2.2.2.1. *Between-groups analysis*

Groups of countries were classified according to their production dynamics, derived from *dY* and *dA*. Fig. 1 presents a diagram of the different groups of countries according to this classification. In this diagram, countries can be in quadrant 1: area and yield increase, quadrant 2: area decrease and yield increase, quadrant 3: area and yield decrease, or in quadrant 4: area increase and yield decrease. We refer to these four groups as follows: “growth” countries with expansion of cultivated area and increasing yield (Q1); “intensifying” countries with contraction of cultivated area but increasing yield (Q2); “decline” countries with contraction of cultivated area and decreasing yield (Q3); and “expansion” countries with expansion of cultivated area but decreasing yield (Q4).

In order to explore differences between these groups in terms of control- and governance indicators, we performed an ANalysis Of VAriance (ANOVA). Specifically, separate T-tests were performed for all possible pairs of different quadrants and indicators, provided that the number of observations was sufficient. This analysis is referred to as the between-groups analysis.

2.2.2.2. *Within-groups analysis*

Next, in order to test the maximal and marginal explanatory value of governance indicators we performed linear regressions, for all countries together and for the groups individually. While the between-groups analysis distinguished countries based on the sign of *dY* and *dA,* the within-groups analysis investigates the spatial variability in *dY* and *dA* values within groups, taking into account their correlation with governance and control indicators. Multivariate regression analysis was applied to examine relationships between governance indicators and *dY* and *dA*. As the number of observations was not high enough to allow for the use of all indicators, a pre-selection of indicators was made (per group and dependents *dY* and *dA*). This was done using the following criteria: only one out of two correlated indicators (i.e., with a Pearson correlation coefficient > 0.65) was kept in the selection. Furthermore, only indicators that were significant ($p \leq 0.05$) in univariate regressions (with *dY* and *dA*) were selected for further analysis. For the governance indicators, a significance level of $p \leq 0.1$ was used, because we assume that the explanatory power of governance variables is often only revealed in combination with other control indicators, i.e., statistical interaction between governance and control indicators. The maximal and marginal explanatory power of the governance indicators were identified. The maximal explanatory power was obtained by using only the governance indicators. The marginal explanatory power was obtained by comparing the model containing all governance and control indicators to a model containing only the control indicators. Furthermore, the signs of the relationships between quality of governance and area- and yield change were determined. This was done by examining whether area- or yield change decreased or increased when all governance indicators increase by a value of 1, i.e., those that were significant.

2.3. Results

2.3.1. ***Between-groups analysis***

All 173 countries were classified based on changes in yield *dY* and cultivated area *dA* as shown in Fig. 1. For any country in the diagram, the position relative to the origin reflects a change in production during 1975–2007, as *dP* is approximated by the sum of *dY* and *dA*. In all countries below the diagonal with negative slope production decreased, while in countries above it production increased. On the diagonal, changes in area and yield offset one another; $dP \approx 0$. On the diagonal with positive slope, changes in production are not dominantly attributable to either changes in area or changes in yield; $dA = dY$. Below it, $dA > dY$, and above it, $dA < dY$.

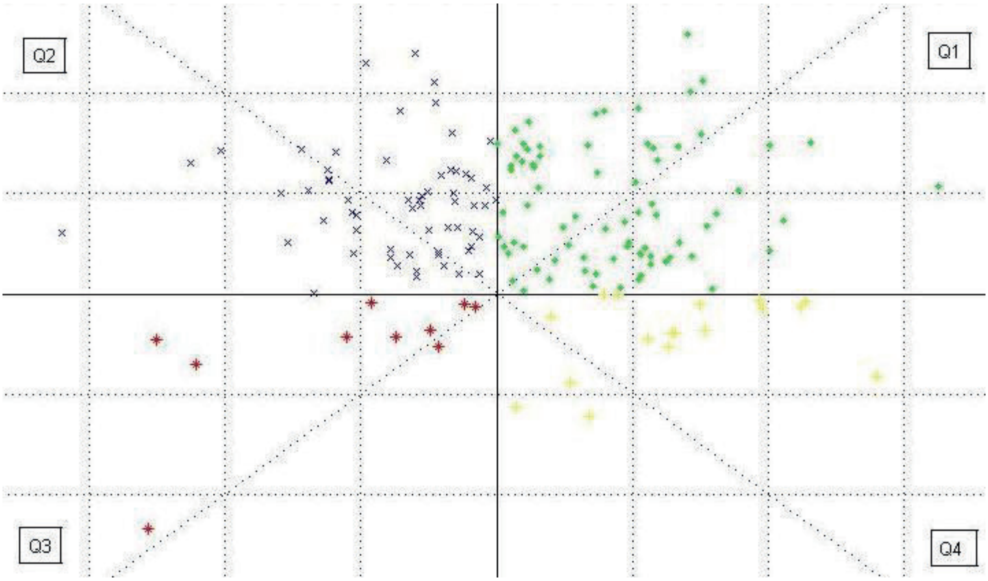


Fig. 1. Log of relative change in yield (*dY*) and log of relative change in cultivated area (*dA*) on the y- and x-axis respectively (both at national level), for 173 countries ($dP \approx dY + dA$). Q1 holds "growth" countries, Q2 "intensifying" countries, Q3 "decline" countries and Q4 "expansion" countries (see methods: between-groups analysis).

From Fig. 1 it becomes clear that countries with a yield decline are a minority. Fig. 2 shows that total areas of "decline" and "expansion" countries are negligible compared to that of "growth" and/or "intensifying" countries, and that "growth" and "intensifying" countries roughly divide the area in two. Furthermore, most "growth" countries are developing or industrializing countries. Mexico, most of South America, most of Africa, most of the Middle East and South East Asia, but also Canada, Australia, France and Norway are in the "growth" quadrant. Canada and Australia are developed and wealthy countries in which land is abundant, and therefore a cheap resource. France and Norway negligibly increased their cultivated area and are bordering between "growth" and "intensifying" behavior. Conversely, the bulk of "intensifying" countries is made up by industrializing to developed countries. Most of Europe, New Zealand, the United States of America, small parts of South America:

Colombia, Ecuador, Peru, Chile and Uruguay; China, Japan, Turkey, some of the wealthier African countries: Algeria, Libya, Morocco, Botswana and South Africa; but also Afghanistan, Yemen and the African countries of Senegal, Cameroon, Republic of the Congo, and Somalia are in the "intensifying" quadrant. These last few countries clearly deviate from the bulk of "intensifying" countries in terms of wealth and development.

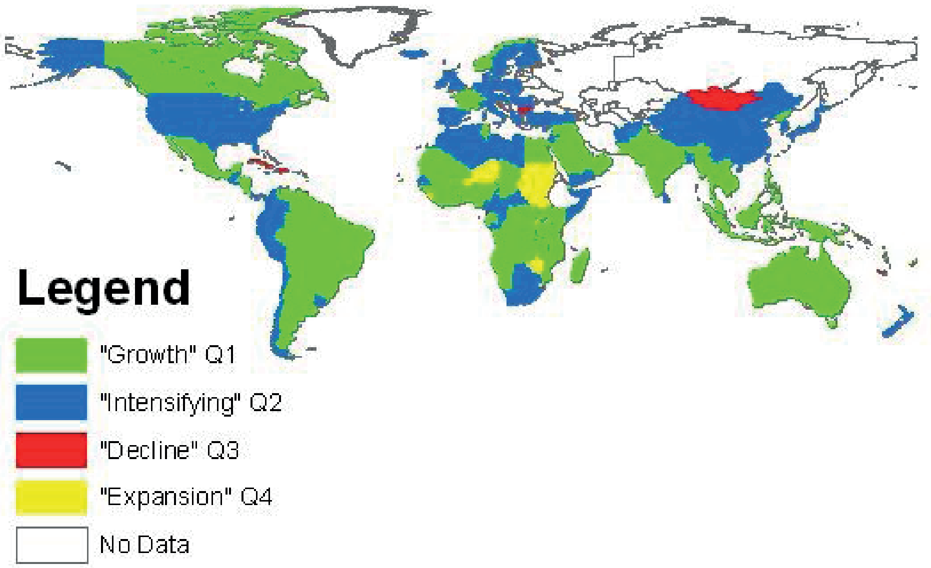


Fig. 2. Geographical representation of the four groups of countries, depending on the signs of *dY* (log of relative change in yield at national level) and *dA* (log of relative change in cultivated area at national level).

Table 2 shows means and significant differences in means of the different indicators, between the groups of countries. For those indicators that were not significantly different with respect to other quadrants, only the means are given.

Table 2. Between-groups analysis of means.

	Growth (Q1), N = 80	Intensifying (Q2), N = 65	Decline (Q3),N = 10	Expansion (Q4), N = 18	All, N = 173
Governance indicators					
Voice and accountability	-0.25 (Q2***)	0.32 (Q1***, Q4*)	-0.02	-0.14 (Q2*)	-0.01
Government effectiveness	-0.25 (Q2***)	0.43 (Q1***, Q4***)	-0.22	-0.38 (Q2***)	-0.001
Regulatory quality	-0.26 (Q2***)	0.41 (Q1***, Q4***)	-0.11	-0.45 (Q2***)	-0.01
Rule of law	-0.23 (Q2***)	0.34 (Q1***, Q4*)	-0.26	-0.18 (Q2*)	-0.01
Political stability	-0.19 (Q2*, Q3**)	0.08 (Q1*)	0.27 (Q1**)	0.00	-0.04
Control of corruption	-0.25 (Q2***)	0.4 (Q1***, Q4**)	-0.27	-0.18 (Q2**)	0.01
Control indicators					
Economic					
Change in agricultural export value index	0.53	0.51	0.04	0.07	0.44
Initial agricultural export value index (share of total export value)	237.46	113.47 (Q4*)	175.50	286.39 (Q2*)	187.89
Change in agricultural import value index	0.77 (Q3*)	0.73	0.61 (Q1*)	0.70	0.74
Initial agricultural import value index (share of total import value)	44.50	44.08	63.48	51.41	46.38
Change in net trade flow value (export minus import)	-0.08 (Q4**)	-0.14 (Q4*)	-0.28	-0.51 (Q1**, Q2*)	-0.16
Initial net trade flow value (export minus import) (share of total value)	182.20	69.39 (Q4*)	112.02	234.97 (Q2*)	137.92
Change in GDP (PPP)	0.57 (Q2***)	0.7 (Q1***)	0.72	0.46	0.62
Initial GDP (PPP) (International $/capita/yr)	2880.80 (Q4***)	4006.30 (Q4***)	2678.10	907 (Q1***, Q2***)	3275.40
Change in economically active agricultural population	0.11 (Q2***)	-0.15 (Q1***, Q4***)	-0.10	0.16 (Q2***)	0.01
Initial economically active agricultural population (share of total)	0.51 (Q2***, Q3**)	0.32 (Q1***, Q4***)	0.36 (Q1**, Q4**)	0.55 (Q2***, Q3**)	0.43
Demographic					
Change in total population	0.32 (Q2***)	0.18 (Q1***)	0.17	0.26	0.25
Initial total population density (persons/Km2)	79 (Q2*)	176 (Q1*, Q3*, Q4*)	80 (Q2*)	82 (Q2*)	116
Change in total economically active population	0.33 (Q2***)	0.21 (Q1***, Q4*)	0.22	0.28 (Q2*)	0.27
Initial economically active population (share of total)	0.39 (Q4**)	0.40 (Q4**)	0.38	0.36 (Q1**, Q2**)	0.39

Change in urban population	0.19 (Q2***, Q3***)	0.11 (Q1***)	0.07 (Q1***, Q4***)	0.23 (Q3***)	0.16
Initial urban population (share of total)	0.39 (Q2***)	0.54 (Q1***, Q4***)	0.47 (Q4*)	0.32 (Q2***, Q3*)	0.44
Change in rural population	-0.17 (Q3*)	-0.16	-0.10 (Q1*)	-0.14	-0.16
Initial rural population (share of total)	0.61 (Q2***)	0.46 (Q1***, Q4***)	0.53 (Q4*)	0.68 (Q2***, Q3*)	0.56
Biophysical					
Annual mean temperature (°C)	22.80 (Q2***)	17.60 (Q1***, Q4***)	20.40	24.10 (Q2***)	20.80
Annual precipitation (mm)	1361.60	1140.00	1475.70	1273.50	1274.20
Fraction of area constrained by aluminum toxicity	22.30 (Q2**)	14.60 (Q1**)	25.50	19.90	19.20
Fraction of area constrained by salinity	4.20 (Q2**)	1.70 (Q1**)	3	1.30	3
Fraction of area constrained by high phosphorus fixation	6 (Q2***)	2 (Q1***)	9.20	6.40	4.50

Mean values of indicators per quadrant, and in parentheses from which other quadrants means significantly differ, according to T-tests. On the right, total means of these variables. $p \leq 0.1^{*}$, $p \leq 0.05^{**}$, $p \leq 0.01^{***}$ Statistical software: R for statistical computing version 2.8.0 (2008).

With respect to governance, Table 2 shows that differences between “growth” countries and “intensifying” countries are most significant, and also that numbers of observations for these two groups are highest. Furthermore, “expansion” countries differ strongly from “intensifying” countries, as all but one governance indicators differ significantly. On average, high quality of governance is mostly seen in “intensifying” countries, far above global average in general. The average quality of governance is significantly lower in the other groups. Remarkable is that “decline” countries distinguish themselves from other groups by their relatively high “political stability”. “Growth” and “intensifying” countries differ in terms of biophysical control indicators as well. “Growth” countries are warmer and have more severe biophysical constraints than “intensifying” countries. The present welfare level in “intensifying” countries is at ca. \$ 20,100 per capita per year, compared to ca. \$ 14,050 per capita per year for “decline” countries. The present welfare levels in “growth” and “expansion” countries are at ca. \$ 10,700 per capita per year and ca. \$ 2,600 per capita per year, respectively. Contrary to “intensifying” and “decline” countries, agricultural labor force strongly increased for “expansion” and “growth” countries. Finally, initial population density was almost twice as large for “intensifying” countries, compared to the other groups.

2.3.2. *Within-groups analysis*

The within-groups analysis could only be performed for the total number of countries, and for the "growth" and "intensifying" countries, as there were not sufficient observations for "decline" and "expansion" countries for reliable regressions; n = 10 and n = 18 respectively. Table 3 presents how well the variance of production indicators is explained by the biophysical, demographic and economic control classes (separately and together), and how well it is explained by governance (maximally and marginally).

Table 3. Variance explained (R^2) by classes and combinations of classes, per quadrant and dependent. *dY* is the log of relative change in yield at national level, and *dA* the log of relative change in cultivated area at national level.

	Growth (Q1), N = 80		**Intensifying (Q2), N = 65**		**All, N = 173**	
Control classes	***dA***	***dY***	***dA***	***dY***	***dA***	***dY***
Economic (E)	0.65	0.35	0.39	0.07	0.20	0.25
Demographic (D)	0.56	N.S.	0.20	N.S.	0.34	N.S.
Biophysical (B)	0.33	0.13	N.S.	N.S.	0.31	0.04
(E) + (D) + (B)	0.75	0.36	0.56	0.07	0.48	0.27
Governance classes						
Maximal governance (G)	0.19	0.09	0.08	0.07	0.07	0.09
Marginal governance (E+D+B+G)-(E+D+B)	0.03	0.02	0.00	0.22	0.04	0.02
Sign of relationship	-	+	-	+	-	+

N.S. = Not Significant. Sign of relationship refers to whether *dA* or *dY* decreases (negative) or increases (positive), upon increasing the quality of governance in the maximal governance class regression equations. Statistical software: R for statistical computing version 2.8.0 (2008).

Area increases are strongly controlled by economic and demographic indicators for "growth" countries (Table 3). Yield increase could be less well described, but also seems to be controlled mostly by economic indicators. Governance explains between 3 and 19 % of variance of change in cultivated area and between 2 and 9 % of variance of change in yield. The sign of the relationship between governance and area change is negative, meaning that the higher the quality of governance, the lower the area increase. The relationship between governance and yield change is positive, meaning that the higher the quality of governance, the higher the yield increase. For "intensifying" countries, economic indicators appear to be important determinants as well. It is striking that biophysical constraints do not seem to play a role for these countries. Governance explains between 0 and 8 % of variance of area decrease and between 7 and 22 % of variance of yield increase. For yield increase, the maximal governance class gives a lower value of explained variance than the marginal governance class, which points to interactions between the governance- and control indicators. The sign of the relationship between governance and area decrease is again negative, indicating that better governance is associated to stronger area decreases. The sign of the relationship between governance and yield increase is again positive. Clearly, the bandwidth of variance explained by governance is higher for area increase for "growth" countries, and higher for yield increase for "intensifying" countries, roughly in opposite magnitudes.

For all groups combined, economic factors explain a significant part of the global variance in changes in area and yield. Area changes are also determined by demographic and biophysical constraints. Governance explains between 4 and 7 % of variance of change in cultivated area and between 2 and 9 % of variance of change in yield, similar to results found by others (Kok and Veldkamp 2001). The bandwidths of variance explained by governance are now in the same range of magnitude. The signs of the relationships are again negative for area change, and positive for yield change.

2.4. Discussion

The results from the two analyses presented here confirm the hypothesis that in countries with lower quality of governance, agricultural production increase is more likely to be achieved by area expansion than by increase in yield. Although governance indicators do not explain vast shares of spatial variability in cultivated area- and yield change within groups, a nonzero marginal explanatory value considerably increases the likelihood that governance does matter. In reality, the strengths of relationships are likely to be somewhere in between the most strictly (marginal R^2) and loosely held criteria (maximal R^2). Overall, the chosen set of control indicators seems adequate in explaining spatial variability in production indicators other than governance indicators, because of the overall consistency of results. Evidently, control and governance indicators can never be entirely separated, and interaction is likely to be present in the real world (e.g., countries with poor governance suffering more from a harsh climate than countries with a similar climate but good governance). In the case of yield change in "intensifying" countries interaction is even such that marginal explanatory power exceeds maximal explanatory power.

From Table 2 we could tell that quality of governance in “growth” countries differs most from that in “intensifying” countries, and that “expansion” countries also differ strongly from “intensifying” countries in this respect. Furthermore, quality of governance is high in “intensifying” countries and low in other groups. In between groups, significantly higher quality of governance does not necessarily lead to a significantly higher yield increase, as average yield increases were nearly identical for “growth” and “intensifying” countries, which is not shown. However, the between-groups analysis does indicate a relationship between lower quality of governance and stronger area increase, for “growth” and “intensifying” countries. This means that the lower the quality of governance, the more area increase will occur. The signs of relationships found in the within-groups analysis confirm this by suggesting that lower quality of governance is more associated with area increase than with yield increase, while higher quality of governance is now also more associated with yield increase than with area increase (Table 3). We also know that quality of governance seems more important to the explanation of spatial variability in area increase in “growth” countries, and more important to the explanation of spatial variability in yield increase in “intensifying” countries (Table 3). Therefore, in general, higher quality of governance seems to lead to substitution behavior of land for inputs, rather than increases in yield only. This expands on previous studies that only showed yields to be positively related to higher quality of governance (Lio and Liu, 2008; Thirtle and Piesse, 2007; Fulginiti et al., 2004). As for the individual governance indicators, it could be seen that the scores on political stability differ from those of the other governance indicators (i.e., relatively low likelihood of destabilization in “growth” countries, when compared to “intensifying” countries; Table 2). This indicator is more independent from the others anyway: one may have poor governance but without much violence (Table 2). On the other hand, political instability is unlikely to occur in combination with good governance.

These results suggest that countries with lower quality of governance are more oriented towards expansion, and that rising levels of production are achieved more by area increase than by yield increase. Moreover, as quality of governance becomes higher, this orientation of countries towards production tends to flip from expansion towards intensification. This indicates that it is not possible to prevent further expansion in “growth” countries, unless quality of governance can be improved. On the contrary, rising levels of production would likely be accompanied by approximately equally as much expansion as yield growth, in line with other global studies (Bindraban et al., 2009; OECD/FAO, 2008; IAASTD, 2009). If quality of governance could be increased, results suggest that less cultivated area could be used than at present by “growth” countries. Furthermore, in “growth” countries, quality of governance could still rise radically, compared to “intensifying” countries. Therefore, “growth” countries appear to have a large potential for further substitution of agricultural production. The “intensifying” countries, which are generally wealthier and more developed (Fig 2, Table 2) than “growth” countries, seem to have realized this potential to a large extent already. Moreover, yield increases could be realized more cost-effectively in “growth” countries than in “intensifying” countries (Marra et al., 2003), as “growth” countries are generally less developed than “intensifying” countries (Fig 2, Table 2). That economic- and governance indicators appear to interact for yield change in “intensifying” countries (Table 3), could reflect that “intensifying” countries are generally higher up on their technological learning curve (Marra et al., 2003). Finally, “intensifying” countries are less biophysically constrained, which could also be related to a higher level of technology, knowledge and more effective management.

2.5. Conclusions

It was demonstrated that governance in countries where the agricultural area expands, differs significantly from that in countries where the agricultural area contracts. Governance is more important to the explanation of spatial variability in area increase in less well-developed countries, and more important to the explanation of spatial variability in yield increase in more highly developed countries. This indicates that in the first case governance is more related to expansion, and in the latter more to intensification. Furthermore, our analysis suggests that countries with poor governance are more likely to achieve a production increase by means of area expansion rather than by means of yield increase. Moreover, as the quality of governance increases, this orientation towards production tends to flip from expansion towards intensification. Should we assume a causal relationship, the tendency of expanding cultivated area in less developed countries can be stopped by improving the quality of governance.

I stand on your horizon,
True love is on the run,
Chasing ever after your shadow,
Dancing on the dark side of my sun.

3

Quantifying effects of governance on nature dynamics in Europe: A cross-national comparison for 1990–2006

Resubmitted to Land Use Policy (after revisions):
Mandemaker. M, Bakker, M., Jongman, R., and Veldkamp, A., 2014.

Abstract

In this study, quantitative relationships between overall quality of governance and processes of fragmentation and expansion of nature were studied through cross-national comparison for 20 European countries for the period 1990–2006. Land-cover change trends were detected by comparing CORINE land-cover maps from the years 1990 and 2006. Four dominant spatiotemporal processes of change in nature were revealed by characterizing past developments with two indicators: overall change in nature area and change in average patch size of nature. These processes were "Formation of larger-than-average patches of nature and/or Expansion of nature and/or Connection of nature"; "Formation of smaller-than-average patches of nature"; "Removal of smaller-than-average patches of nature"; and "Removal of larger-than-average patches of nature and/or Shrinkage of nature and/or Dissection of nature". The majority of countries expanded their total nature, although this is likely not to have been the result of deliberate nature restoration alone but also of land abandonment or afforestation for production purposes, which do not necessarily lead to positive development in terms of biodiversity. For the period 1990–2006, overall quality of governance was found to be positively related to expansion of nature, and negatively to increasing patch size of nature. Lower scores of overall quality of governance are more likely to drive the processes of removal, shrinkage, and dissection of nature through changes in nature area. Higher scores of overall quality of governance are more likely to drive the processes of formation, expansion, and connection of nature through changes in both nature area and patch size. Overall, quality of governance could indeed drive the deliberate development of nature for the purposes of restoration and conservation, halting fragmentation and the ongoing decline of biodiversity in Europe.

Keywords: biodiversity; structural connectivity; governance; policy; land-cover pattern; ecological network.

3.1. Introduction

Current rates of fragmentation of European nature areas pose a major threat to the survival of species that depend on their ability to disperse or migrate into other habitats (EEA, 2011; Van der Sluis et al., 2012). Throughout the 1990s and the first decade of the 21st century, there have been many actions to combat this threat at EU level, at national levels, and at sub-national levels. Proposed solutions have been primarily scientific and technical, focusing on the development of ecological networks in one form or another (Jongman et al., 2004, 2011). Although designs of these networks were often embedded in a policy context, actual implementation is challenged by how governance is organized in reality, e.g., decentralized or centralized (Von Haaren and Reich, 2006; Čivić et al., 2009; Simeonova et al., 2009). Policy studies on the implementation and evaluation of fragmentation-combating measures often suggest that a lack of quality in governance is responsible for the failure to halt further nature fragmentation (Leibenath et al., 2010). However, these studies are often performed at local level, and although they give detailed accounts of institutional and legislative organization, the sheer complexity as well as the qualitative nature of such accounts prevents cross-national comparisons. Nevertheless, in 2009, the World Bank has defined quantitative dimensions of quality of governance, which have been assessed for nearly all countries in the world (215) in the same manner (Kaufmann et al., 2009, 2010). These dimensions of governance provide quantitative national estimates of the quality of governance during the 1990s and the first decade of the 21st century (Table 1, World Bank, 2014a). Although these are crude estimates of the quality of governance they have been successfully used for quantitative analysis before (Mandemaker et al., 2011), and their international comparability allows for a quantitative analysis of statistical relationships between governance quality and the success in combating nature fragmentation. Results of the proposed analysis may be eligible for meaningful interpretation, because it is plausible that the World Bank dimensions of governance could be related to nature protection- and development, in the following ways.

Nature and ecological richness are often seen as common goods, which need to be protected from overexploitation by private parties, to avoid or resolve classical ‘tragedies of the commons’ (Hardin, 1968; Ostrom, 1990). This is generally done by means of effective formulation and implementation of policies and regulations by a central government, of which the effectiveness is measured by the indicator “Government effectiveness” (Table 1). Furthermore, these policies and regulations should be diligently enforced by law-enforcement agencies, the capacity of which to do so being measured by “Rule of law” (Table 1). Moreover, when enforced policies and regulations are of insufficient quality, measured by “Regulatory quality” (Table 1), private parties may still overexploit the natural areas, which may result in their partial removal or fragmentation. To prevent unsustainable overexploitation, nature areas are often owned by the government (national, provincial, or municipal), but also private owners and Non-Governmental Organizations (NGOs) own or manage the land, often financially supported by the government (Čivić et al., 2009). Those officials charged with the protection of nature areas should not be prone to the temptations of bribery and abusing their position and role by privileging specific private interests that will erode existing nature and harm the functioning of ecosystems, such as clearance for property development or illegal harvesting of wood. The extent to which officials are prone to such temptations is measured by “Control of corruption” (Table 1). This in turn depends on the amount of institutional transparency and the extent to which officials may be held accountable by the public, measured by “Voice and accountability” (Table 1).

The preceding refers to the protection of existing nature areas, but other processes are at play when it comes to actively developing ecological networks. Governments that are involved in such actions have often committed themselves to international agreements, follow national legislation, or are otherwise responding to a call for more nature from citizens (Jones-Walters et al., 2009). The greater the degree to which these stakeholders are allowed to voice environmental concerns and affect decision making through democratic voting processes, also measured by “Voice and accountability” (Table 1), the more likely the realization of nature development. Furthermore, the spatial design of ecological networks is important for effective realization of nature development: the more its design is integrated with ecological knowledge the higher the quality and sustainability of the network (Čivić et al., 2009; Simeonova et al., 2009). However, the actual realization of new nature-conservation targets is another matter. Land that is designated to become nature is often owned by individual stakeholders (e.g., estate owners, farmers), and management agreements have to be made with these landowners or land can be purchased (Čivić et al., 2009), compulsorily in extreme cases (“Rule of law”). It may be clear that this process is fragile and decisions that are considered as good governance from the point of conservation considerations are not always considered as such by the stakeholders involved and vice versa (Čivić et al., 2009; Jones-Walters et al., 2009). This especially applies to cases where regional planning is practiced through multi-stakeholder participative processes where the governance is highly democratic (“Voice and accountability”), but ecological quality depends on how local, regional, and national authorities take their responsibility and on how resulting plans are elaborated (Lawton et al., 2010).

In this study, we test the hypothesis that quality of governance is related to fragmentation and expansion of nature, through cross-national analysis performed over 20 European countries and characterization of dominant spatiotemporal processes of fragmentation and expansion of nature. This characterization enables the identification of different processes of fragmentation and expansion in the field, which might help spatial planners to better understand geographical differences between ecological networks (Čivić et al., 2009). This characterization is based on relative changes in average patch size and total area of nature for each country, analyzed by combining the CORINE 1990 and 2006 land-cover maps (EEA, 2009, 2010). Confirmation of the hypothesis might form an incentive for further, more targeted evaluation of quality of governance.

3.2. Data and methods

3.2.1. *Data*

3.2.1.1. *Indicator of overall quality of governance*

The presented World Bank dimensions of governance (Table 1) are quantified perceptions of state-centric governance, provided by a large number of enterprises, citizens, and expert survey respondents in industrial and developing countries (World Bank, 2014b). These dimensions of governance can be used as indicators in a semi-positivistic approach to studies of how quantified perceptions of state-centric governance relate to spatiotemporal processes of fragmentation of nature (*1.1.2.2.1. Empirical-statistical modeling*). Each dimension of governance was constructed per country by averaging data from the underlying sources that corresponded to the concept of governance being measured (World Bank, 2014a). All indicators have a mean of zero, a standard deviation of one, and a range of-2.5 to 2.5. Higher values correspond to higher quality of governance. For the purpose of this research we computed averages of the World Bank dimensions of governance presented in Table 1, over 1996–2011 for 20 European countries (Table 2).

Table 1. Five World Bank dimensions of governance.

Indicator name	World Bank definition
Voice and accountability	Capturing perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.
Government effectiveness	Capturing perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.
Regulatory quality	Capturing perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.
Rule of law	Capturing perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.
Control of corruption	Capturing perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.

Source: World Bank, http://info.worldbank.org/governance/wgi/index.aspx#home.

Clearly, any results of statistical analyzes involving the World Bank dimensions of governance cannot be interpreted in the sense of their exact definitions (Table 1), as these are far too subtle and complex to be incorporated in crude statistical analyzes. Furthermore, the separate World Bank dimensions are highly correlated between themselves (not shown), further preventing meaningful interpretation in this sense. Moreover, the low number of observations (20) does not allow for reliable multivariate analysis but only for bivariate analysis. For these reasons, we aimed to capture the five WB indicators into one summary indicator. This indicator was obtained by doing a Principal Component Analysis (PCA) of the 15-year averages of the presented dimensions of governance (Tables 1–2). This way, one new summary indicator was obtained that is a linear combination of all five original indicators, but which contains maximal variance for our subset of 20 European countries.

Table 2. Averages of World Bank dimensions of governance over 1996–2011.

Country code	VA (-)	GE (-)	RQ (-)	RL (-)	CC (-)
AU	1.39	1.85	1.55	1.85	1.93
BU	0.51	0.01	0.49	-0.18	-0.19
BX	1.46	1.78	1.50	1.55	1.55
CZ	0.95	0.89	1.10	0.85	0.36
DK	1.60	2.16	1.82	1.91	2.44
ES	1.04	0.96	1.36	0.91	0.77
FR	1.25	1.58	1.13	1.41	1.38
GE	1.36	1.65	1.49	1.64	1.85
HU	1.04	0.84	1.11	0.84	0.53
IL	1.39	1.57	1.72	1.64	1.59
IT	1.04	0.60	0.90	0.55	0.30
LA	0.76	0.52	0.95	0.53	0.04
LI	0.87	0.58	1.01	0.55	0.15
NL	1.57	1.90	1.81	1.75	2.15
PL	0.97	0.57	0.79	0.57	0.38
PO	1.32	1.06	1.08	1.13	1.13
RO	0.41	-0.30	0.32	-0.10	-0.28
SK	0.87	0.76	0.94	0.42	0.28
SL	1.09	0.97	0.83	0.99	0.97
SP	1.20	1.33	1.23	1.20	1.18

VA = "Voice and accountability", GE = "Government effectiveness", RQ = "Regulatory quality", RL = "Rule of law", and CC = "Control of corruption". AU = Austria, BU = Bulgaria, BX = Belgium-Luxembourg, CZ = Czech Republic, DK = Denmark, ES = Estonia, FR = France, GE = Germany, HU = Hungary, IL = Ireland, IT = Italy, LA = Latvia, LI = Lithuania, NL = the Netherlands, PL = Poland, PO = Portugal, RO = Romania, SK = Slovakia, SL = Slovenia, and SP = Spain. Belgium and Luxembourg were merged into Belgium-Luxembourg (BX) for technical reasons. Source: World Bank, http://info.worldbank.org/governance/wgi/index.aspx#home.

Table 3. Coefficients of linear contribution to the first principal component of governance, and Pearson correlations between separate dimensions of governance, and the predicted score of overall quality of governance based on the first principal component.

	VA	*GE*	*RQ*	*RL*	*CC*
Coeff. of contribution to PC 1	0.45	0.45	0.44	0.45	0.45
Pearson corr. coeff.	0.98	0.99	0.95	0.99	0.98

PC 1 = Principal Component 1, *VA* = "Voice and accountability", *GE* = "Government effectiveness", *RQ* = "Regulatory quality", *RL* = "Rule of law", and *CC* = "Control of corruption".

The first principal component explained ca. 96 % of cumulative variance, i.e., contributions of higher-order principal components were negligible and therefore not shown. This component was used as a summary indicator, i.e., as an indicator of overall quality of governance.

3.2.1.2. *CORINE Land Cover (CLC)*

The first CORINE land-cover map based on an inventory of 44 land-cover classes (see *Appendix*) was presented in 1990 (EEA, 2010). To produce the CORINE 2000 land-cover map, the existing CORINE 1990 land-cover map was first assessed and corrected for geometric- and thematic content (EEA, 2009). Land-cover changes were mapped by using satellite images- and ancillary data from the year 2000 (Feranec et al., 2010). That is, the two land-cover maps were made comparable to produce a dataset of land-cover change for 1990 – 2000 (EEA, 2012a). In turn, the CORINE 2006 land-cover map resulted from updating the CORINE 2000 land-cover map in a comparable way, to produce a dataset of land-cover change for 2000–2006 (EEA, 2009, 2012b). For the purposes of this research, both the CORINE 1990- and 2006 land-cover maps have been used at a pixel size of 250 m (EEA, 2009, 2010). A shape file of the 20 European countries (Fig. 1) was overlaid on these land-cover maps in ArcGIS 10.1 to obtain separate maps for each country, so that reclassifications could be made to include specific land-cover classes in specific categories. To analyze change in natural- and semi-natural land cover, we included the non-urban and non-agricultural land-cover classes ranging from '3.1.1. – Broad-leaved forest' through '3.2.4. – Transitional wood-land shrub', and '3.3.3. Sparsely vegetated areas' (see *Appendix*). These analyzed land-cover classes together form the terrestrial vegetated non-agricultural and non-urban land cover. As these vegetated land-cover classes can all play a role as habitat and in structural connectivity, we defined this set of land-cover classes as *nature* within this study, precluding other forms of nature such as water bodies, urban parks, etc. Here it is emphasized that although this definition of nature is clearly far from complete, it also does not claim to be. Here it should also be emphasized that only structural landscape changes and possible effects on structural connectivity were analyzed (Tischendorf and Fahrig, 2000).

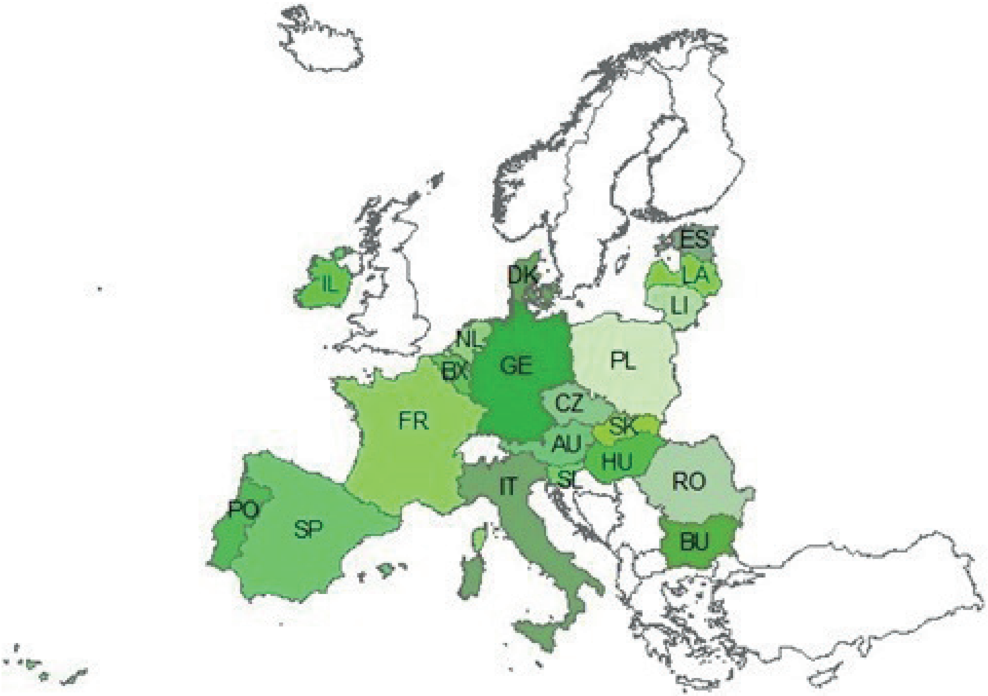


Fig. 1. Geographical representation of analyzed countries (white indicates no data). See Table 2 for country codes.

3.2.2. *Methods*

3.2.2.1. *Change in average patch size and total area of nature*

In order to obtain information on patch size of nature areas (*PSN*), we converted the nature grids into polygon shape files. When two (clusters of) nature pixels only met at one corner, they were converted to two separate polygons. We assessed the average *PSN* in each country for both 1990 and 2006 and computed the relative change in *PSN* during that period:

$$\delta PSN \equiv \frac{PSN(2006) - PSN(1990)}{PSN(1990)}. \quad (1)$$

In Eq. 1, δPSN is the relative change in average patch size of nature, $PSN(1990)$ is the average patch size of nature in 1990, and $PSN(2006)$ is the average patch size of nature in 2006.

In order to obtain information on total nature area (*TNA*) we assessed total nature area for each country in 1990 and 2006, and assessed the relative change in *TNA* during that period:

$$\delta TNA \equiv \frac{TNA(2006)-TNA(1990)}{TNA(1990)}. \tag{2}$$

In Eq. 2, δTNA is relative change in total nature area, $TNA(1990)$ is total nature area in 1990, and $TNA(2006)$ is total nature area in 2006.

Combining δTNA and δPSN, we constructed a characterization of dominant spatiotemporal processes of fragmentation and expansion of nature (Fig. 2).

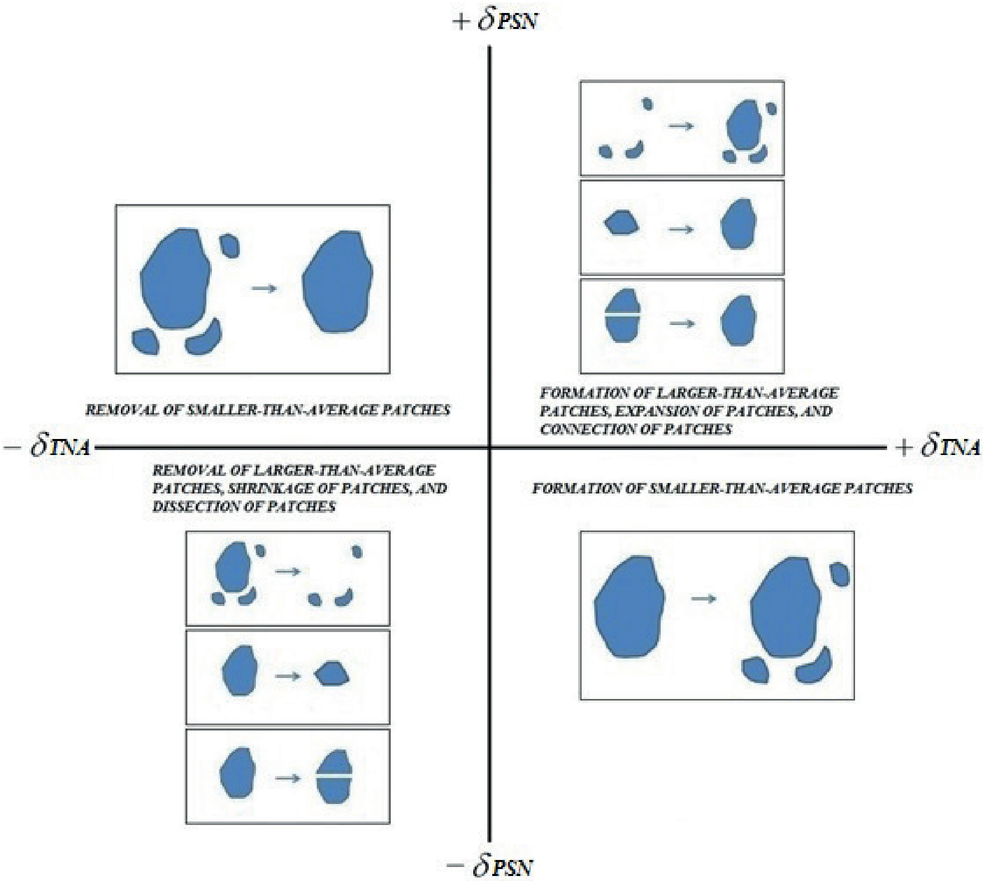


Fig. 2. Characterization of dominant spatiotemporal processes of fragmentation and expansion of nature, with δTNA representing the relative change in total nature area (on the x-axis), and δPSN representing the relative change in average patch size (on the y-axis).

In Fig. 2, δTNA is depicted on the x-axis and δPSN on the y-axis. In the quadrants right of the origin there is increase in nature. In the upper-right quadrant this increase is accompanied by an increase in average patch size. Here are three possible dominant processes: formation of predominantly larger-than-average patches (upper); a net expansion of existing patches of nature (middle); or a net increase in connectedness of existing patches of nature (lower). The formation of larger-than-average patches may not be very likely in real-world cases, given the field-by-field process of nature establishment on previously agricultural areas. In the lower-right quadrant there is increase in total nature, but a decrease in patch size. The only possible process is the formation of more predominantly smaller-than-average patches. In the quadrants left of the origin there is decrease in nature. In the upper-left quadrant there is one dominant process, decrease in total nature, but increase in patch size by removal of predominantly smaller-than-average patches. In the lower-left quadrant there are three possible processes. In general there is a decrease in total nature area as well as a decrease in patch size. This can be removal of predominantly larger-than-average patches (upper); a net shrinkage of existing patches of nature (middle); or a net decrease in connectedness of existing patches of nature by dissection (lower). Here as well, the removal of larger-than-average patches may not be very likely in real-world cases, given the protected status of most of the larger nature areas, in combination with the logistics of such large-scale clearance.

3.2.2.2. *Relationships with overall quality of governance*

Relationships between δTNA and δPSN on the one hand and overall quality of governance on the other, were investigated using Spearman correlation coefficients. Spearman correlation coefficients are defined as Pearson correlation coefficients between ranked continuous data (Siegel, 1957). In this study, Spearman correlation coefficients were computed between overall quality of governance and the indicators of overall change in nature area and change in average patch size of nature. The ranking of these continuous-data valued indicators was done in such a way that the higher the governance score, the higher the rank. Also δTNA and δPSN were ranked, whereby the more positive the change in total nature area, the higher the rank, and the more positive the change in average patch size, the higher the rank. Because 20 countries were included in the analysis, the values of ranked variables range from 1 through 20. Correlations were investigated for the set of all countries, as well as for specific subsets of countries. As the quadrants of Fig. 2 represent different processes, these quadrants were used to divide countries into subsets. The subsets explored are listed in Table 4, and chosen in such a way that the response variables (δTNA and δPSN) maintained a maximal spread, meaning that the relationship between δTNA and governance was explored for the entire range of δTNA, so for the left- and right quadrants together; and that relationships between δPSN and governance were explored for the entire range of δPSN, i.e., for the upper- and lower quadrants together.

Table 4. Subsets for which relationships between governance quality and relative change in average patch size (δPSN)- and/or total nature area (δTNA) were evaluated.

Response variable	Subset	Description
δTNA	LR + LL	Change in total nature area in countries characterized by an overall decrease in the average patch size
δTNA	UR + UL	Change in total nature area in countries characterized by an overall increase in the average patch size
δPSN	UL + LL	Change in average patch size in countries characterized by an overall decrease in total nature area
δPSN	UR + LR	Change in average patch size in countries characterized by an overall increase in total nature area
δTNA	LR + UL	Change in total nature area in countries characterized by removal/formation of predominantly smaller-than-average patches
δTNA	LL + UR	Change in total nature area in countries characterized by removal/formation of predominantly larger-than-average patches; a net shrinkage/expansion of existing patches of nature; or a net decrease/increase in connectedness of existing patches of nature
δPSN	LR + UL	Change in average patch size in countries characterized by removal/formation of predominantly smaller-than-average patches
δPSN	LL + UR	Change in average patch size in countries characterized by removal/formation of predominantly larger-than-average patches; a net shrinkage/expansion of existing patches of nature; or a net decrease/increase in connectedness of existing patches of nature

LL = Lower-left quadrant, LR = Lower-right quadrant, UL = Upper-left quadrant, and UR = Upper-right quadrant (of Fig. 3a).

3.3. Results

3.3.1. ***Characterization of dominant spatiotemporal processes of fragmentation and expansion of nature***

Fig. 3 shows the characterization of dominant spatiotemporal processes of fragmentation and expansion of nature applied on national data for the period 1990–2006. In Poland, Czech Republic, Estonia, Hungary, Latvia, Estonia, and Slovakia both the total nature area and the patch size increased (δTNA and δPSN are both positive). In Austria, Denmark, Germany, Ireland, the Netherlands, Portugal, and Slovenia an increase in total nature area can be observed with a decrease in average patch size (δTNA is positive and δPSN is negative). The decrease in average patch size suggests the formation of new, small nature patches, which may serve as stepping stones for species. In Romania there is a decrease in total nature area combined with an increase in average patch size (δTNA is negative and δPSN

is positive), suggesting that small nature areas have been cleared, possibly by agricultural expansion. In Belgium-Luxembourg, Bulgaria, France, Italy, Lithuania, and Spain the total nature area decreased and so did average patch size (δTNA and δPSN are both negative). These countries show a net shrinkage of existing patches, possibly by urban or agricultural expansion along the edges or by dissection of nature areas by large infrastructure.

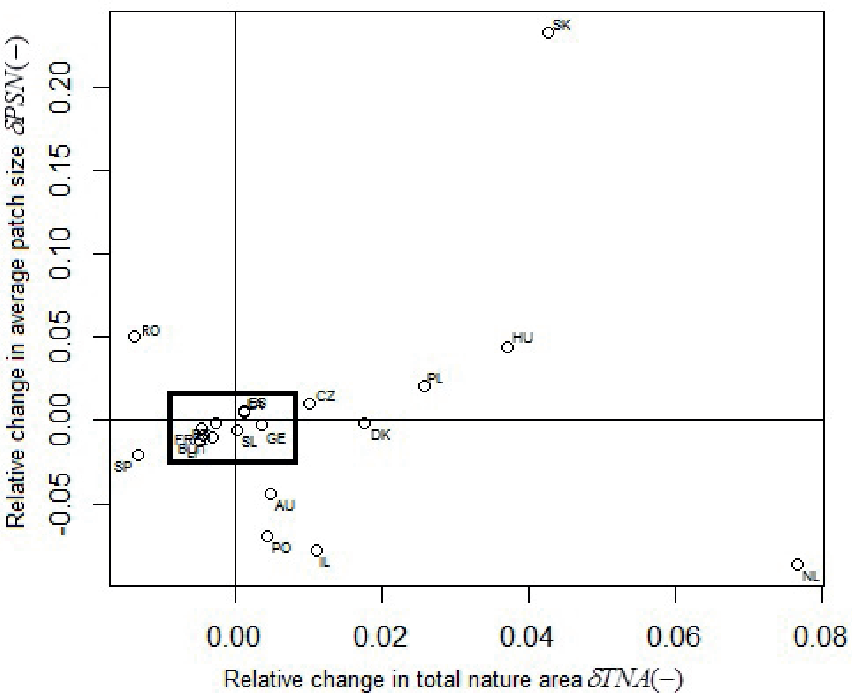


Fig. 3a. Characterization of dominant spatiotemporal processes of fragmentation and expansion of nature applied on real-world data, with δTNA representing the relative change in total nature area (on the x axis), and δPSN representing the relative change in average patch size (on the y axis). See Table 2 for country codes.

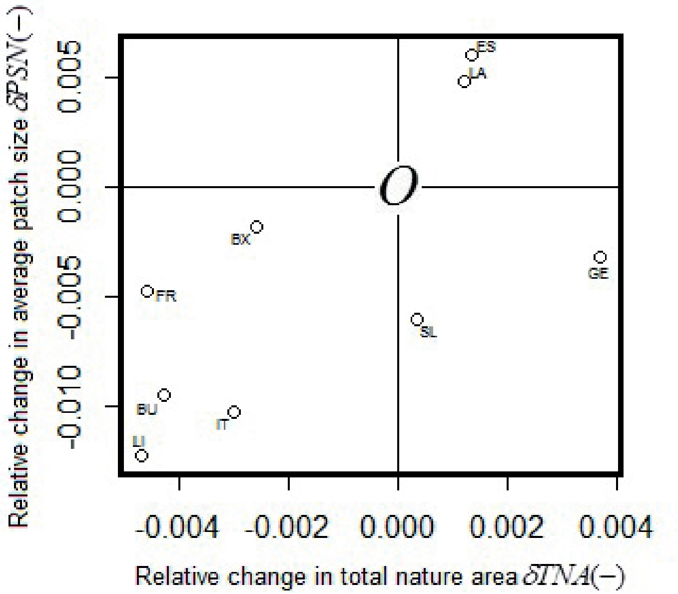


Fig. 3b. Close-up of the area contained in the boldly depicted box, with δTNA representing the relative change in total nature area (on the x axis), and δPSN representing the relative change in average patch size (on the y axis). See Table 2 for country codes.

3.3.2. *Relationships with overall quality of governance*

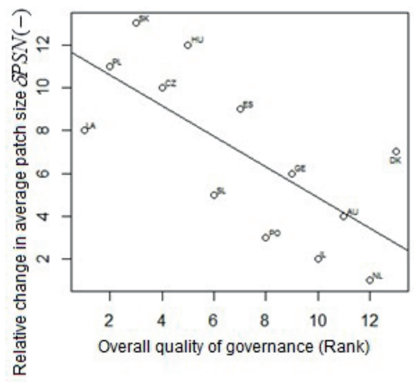
Table 5 shows the subsets for which the strengths of the relationship between quality of governance and δPSN and δTNA have been analyzed. For all countries together applies that the relationship between governance quality and δPSN is fairly strong and significant, while for δTNA it is less strong and less significant. The direction of the relationship between governance quality and δTNA is as expected: the higher the quality of governance, the more the nature area has grown in the period under study. The relationship between governance quality and δPSN is opposite of what we expected: the higher the quality of governance, the more average patch size shrunk. The subset analysis reveals that this is probably due to the countries right of the origin of Fig. 3, so those countries where total nature area increased. The subset analysis (Table 5, Fig. 4) furthermore shows significant relationships between quality of governance and a) δPSN for the lower- and upper-right quadrants; and b) δTNA for the lower-right- and upper-left quadrants; and c) δTNA for the lower-left- and right quadrants. For the lower- and upper-right quadrants, δPSN was significantly negatively related to overall quality of governance. Furthermore, for the lower-right- and upper-left quadrants, δTNA was significantly positively related to overall quality of governance. For the lower-left- and right quadrants, δTNA was significantly positively related to overall quality of governance.

Table 5. Spearman correlation coefficients and R-squared values, for relative change in average patch size ()- and total nature area (), and overall quality of governance.

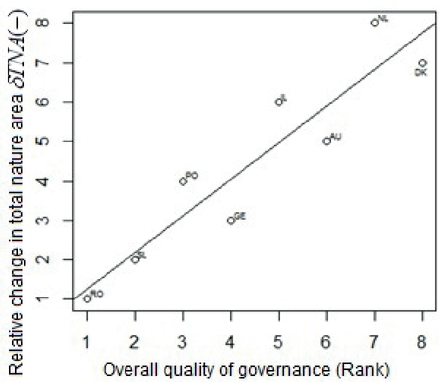
Response variable	Subset	n	Spearman r	R^2
δTNA	-	20	0.36*	0.13
δPSN	-	20	-0.48**	0.23
δTNA	LR + LL	13	0.75***	0.56
δTNA	UR + UL	7	0.46	0.22
δPSN	UL + LL	7	-0.07	0.01
δPSN	UR + LR	13	-0.71***	0.51
δTNA	LR + UL	8	0.93***	0.86
δTNA	LL + UR	12	-0.1	0.01
δPSN	LR + UL	8	-0.33	0.11
δPSN	LL + UR	12	-0.03	0

* indicates p0.1, ** indicates p0.05, *** indicates p0.01; LL = Lower-left quadrant, LR = Lower-right quadrant, UL = Upper-left quadrant, and UR = Upper-right quadrant (of Fig. 3a).

a



b



c

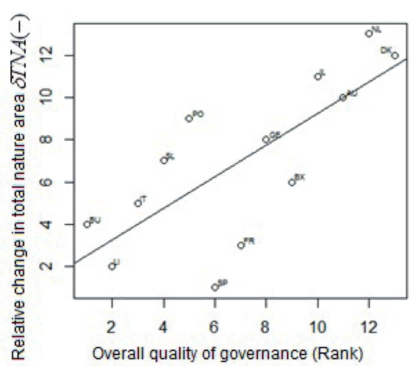


Fig. 4. Scatterplots of those relationships that were significant. The negative relationship between overall quality of governance and relative change in average patch size (δPSN), for the lower- and upper-right quadrants (a); the positive relationship between overall quality of governance and relative change in total nature area (δTNA), for the upper-left- and lower-right quadrants (b); and the positive relationship between overall quality of governance and δTNA, for the lower-left- and right quadrants (c).

3.4. Discussion

The here-presented analysis assesses dynamics in nature areas in Europe and links this to governance aspects. In the period under study considerable changes in land use took place. Most analyzes of the impact of policy (change) on the area and configuration of nature concern case studies or country studies (Mander et al., 1996) and do not provide a comprehensive overview. Conversely, our approach does not provide in-depth detail but the birds' eye view on changes that took place throughout Europe. It is clear from the analysis that (re)development of nature is an important process in many countries. Yet, fragmentation of nature also continues to be increasingly harmful, particularly in countries where this coincides with a decrease in total nature area. The observed trends are in agreement with the trends seen in case studies and expert reports (Petit et al., 2001; Jongman, 2002).

3.4.1. *Characterization of dominant spatiotemporal processes of fragmentation and expansion of nature*

The majority of countries expanded their total nature area during the studied period. Observed trends of nature expansion may have been driven by agricultural land abandonment, by afforestation for commercial purposes, or by ecosystem restoration projects. Although the outcomes can be very different in terms of biodiversity targets, these processes are difficult to disentangle. After all, land abandonment is likely to occur at the fringes of agricultural areas (MacDonald et al., 2000; Hatna and Bakker, 2011), and sometimes deliberate nature development or tree planting for production purposes take place in response to land abandonment. Abandoned farmland and production forests are known to have a relatively low biodiversity in terms of plants and insects, but when they contribute to the enlargement of semi-natural areas they may have led to improved living conditions for larger species. The development of wolves and several large-bird species indeed show that structural connectivity is developing positively for these species (Van der Sluis et al., 2012). Countries that implemented a so-called National Ecological Network , such as in the Czech Republic, Estonia, Poland, and Slovakia (in the upper-right quadrant of Fig. 3), Denmark, Germany, the Netherlands, Portugal, and Slovenia (in the lower-right quadrant) (Jongman et al., 2004) all show an increase in nature area. Whenever nature expansion is the result of such deliberate planning processes, one may expect nature developed at such locations to have a higher biodiversity than the land use it replaced.

Abandonment as the dominant process can be excluded in some countries, where land prices are very high (e.g., Denmark and the Netherlands). Conversely, land abandonment is a serious issue in the Central and Eastern European Countries (CEECs) (mostly in the upper-right quadrant of Fig. 3) (Hobbs and Cramer, 2007), due to major land reforms designed to privatize agricultural land after the fall of the iron curtain (Kuemmerle et al., 2006; Hobbs and Cramer, 2007; Bakker et al., 2011).

The remaining minority of countries showed a decline in their total nature area during the studied period. While it was difficult to tell to what extent the developments have been negative for biodiversity in these countries, it will most certainly not have been a positive development either. Spain and Romania are the outliers of those countries that saw their nature area shrink. Romania is the only country where this resulted in an increase in the average patch size, which has probably been the result of deforestation for the sake of large-scale agriculture in response to Romania's accession to the EU and consequent access to agricultural subsidies. As for Spain, this is also one of the few European countries (together with Bulgaria, France, Italy, and Romania) that showed a net expansion of agricultural land (Bakker and Veldkamp, 2012). Moreover, the strong urbanization/infrastructure development that occurred in Spain may have contributed to its fragmentation of nature as well. However, which of these processes (agricultural expansion or urbanization/infrastructure development) has been dominant in the process of fragmentation could not be determined

3.4.2. *Relationships with overall quality of governance*

Linking the position of the countries within the scheme of Fig. 3 to the indicator of overall quality of governance, reveals how the different underlying processes of fragmentation and/or expansion were related to overall quality of governance. This tends to be lower for countries in the upper-right quadrant, compared to those in the lower-right quadrant (Table 5, Fig. 4), which agrees with the negative relationship found between patch size and overall quality of governance. There is more than one possible explanation for lower (higher) overall quality of governance being associated with an increase (decrease) in the average patch size of nature in the upper-right (lower-right) quadrant of Fig. 3. One is the earlier mentioned abandonment of grasslands in the CEECs, particularly at the boundaries of nature areas (Kuemmerle et al., 2006; Hobbs and Cramer, 2007; Bakker et al., 2011). Another explanation is that nature development in CEES may be realized more efficiently by deliberate planning practices in these countries because property rights of farmers are less well protected there. These explanations together provide an image consistent with what may have occurred in the upper-right quadrant of Fig. 3: a mixture of nature expansion through land abandonment and deliberate development of nature, in which land abandonment has likely been the dominant process (Hobbs and Cramer, 2007). Conversely, when a government plans a nature area, expropriation of its owners is not easy, particularly in the (mostly western European) countries where property rights of farmers are well established and protected. Compulsory purchase for purposes of nature development hardly ever happens (Roodbol-Mekkes et al., 2012), and for that reason deliberate nature development tends to occur according to a more scattered pattern (Bakker et al., Forthcoming). That is, the good protection of land-property rights of farmers in (mostly western European) countries, likely reflected by the higher overall quality of governance in the lower-right quadrant may have hampered deliberate development of nature, which in turn may have had a negative effect on structural connectivity, and ultimately, on biodiversity. On the one hand, nature expansion due to land abandonment may have led to the destruction of high-value agri-ecosystems, but this is more likely to be observed in the upper-right quadrant than in the lower-right quadrant of Fig. 3 (Hobbs and Cramer, 2007). On the other hand, it is highly unlikely that new agricultural areas could have provided a habitat for endangered species in countries where the opposite occurred, i.e., where the dominant land-cover change has been the clearing of nature for agricultural expansion. That latter process is more likely to be observed in the upper-left (and possibly also in the lower-left) quadrant than in the lower-right quadrant of Fig. 3.

3.4.3. *Limitations of this study and suggestions for further research*

Although our analysis provides several interesting results, it is also subject to several handicaps. As mentioned earlier, the lumped-nature category obtained from the CORINE land-cover maps does not allow for distinguishing between deliberately planned nature and that which arose from land abandonment or the establishment of production forest. Although these land-cover types also provide habitats or at least facilitate migration of species to some degree, the establishment of these land-cover types is not the result of deliberate planning and should therefore not be associated with high overall quality of governance. Furthermore, the CORINE land-cover maps do not allow for identification of high-nature value farmland or farmland comprising agri-environment schemes, nor does their resolution allow the evaluation of finer patterns of stepping stones (smaller patches of nature meant to facilitate dispersal).

Moreover, quality of governance is known to be entangled with practically all policy-based drivers of land use, such as rates of agricultural intensification, economic performance, urbanization rates and patterns, etc., making comparative study of correlation coefficients meaningless (Mandemaker et al., 2011). Disentangling the role of governance requires specific statistical techniques to establish both a lower- and upper limit of explanatory power through multivariate analysis, and therefore requires a number of observations that is in the order of ten times larger than was available for this study (Mandemaker et al., 2011). Therefore, and because of the crude nature of the overall quality of governance indicator, it is not possible to confirm the hypothesis that governance is *causally* related to fragmentation and/or expansion of nature. On the other hand, the results of the here-presented analysis do provide empirical evidence in support of this hypothesis, and the analysis allows for generic interpretation of found relationships between quality of governance and fragmentation and/or expansion at the European level, which would otherwise not have been possible. Further research based on more detailed governance indicators with respect to nature conservation and fragmentation could provide better information on how to halt the ongoing decline of biodiversity in Europe, through knowledge generated by quantitative analyzes of relationships between such new, more targeted environmental-governance indicators and identified processes of fragmentation and expansion of nature.

3.5. Conclusions

The here-presented analysis reveals how countries have been performing with respect to development of nature areas by a) characterizing dominant processes of fragmentation and expansion of nature with indicators of overall change in nature area and change in average patch size, and b) by relating these two indicators to overall quality of governance. The majority of studied European countries expanded their nature area, although this is likely not to have been the result of deliberate nature restoration alone but also of land abandonment and establishment of production forest, which do not necessarily lead to positive developments in terms of biodiversity. The remaining minority of studied European countries contracted their total nature area. For the period 1990–2006, overall quality of governance was found to be positively related to expansion of nature, and negatively to increasing patch size of nature. Deliberate development of nature appears to result in formation of smaller-than-average patches of nature, while land abandonment appears to result in the formation of larger-than-average patches of nature. Lower scores of overall quality of governance are more likely to drive the processes of removal, shrinkage, and dissection of nature through changes in nature area. Higher scores of overall quality of governance are more likely to drive the processes of formation, expansion, and connection of nature through changes in both nature area and patch size. Overall, it appears that quality of governance indeed drives the deliberate development of nature for the purposes of restoration and conservation, halting fragmentation and the ongoing decline of biodiversity in Europe.

Appendix

Table 1. CORINE land-cover classes.

Level 1	Level 2	Level 3
1. Artificial surfaces	1.1. Urban fabric	1.1.1. Continuous urban fabric
		1.1.2. Discontinuous urban fabric
	1.2. Industrial, commercial, and transport units	1.2.1. Industrial or commercial units
		1.2.2. Road and rail networks, and associated land
		1.2.3. Port areas
		1.2.4. Airports
	1.3. Mine, dump, and construction sites	1.3.1. Mineral extraction sites
		1.3.2. Dump sites
		1.3.3.Construction sites
	1.4. Artificial, non-agricultural vegetated areas	1.4.1. Green urban areas
		1.4.2. Sport and leisure facilities
2. Agricultural areas	2.1. Arable land	2.1.1. Non-irrigated arable land
		2.1.2. Permanently irrigated land
		2.1.3. Rice fields
	2.2. Permanent crops	2.2.1. Vineyards
		2.2.2. Fruit trees and berry plantations
		2.2.3. Olive groves
	2.3. Pastures	2.3.1. Pastures
	2.4. Heterogeneous agricultural areas	2.4.1. Animal crops associated with permanent crops
		2.4.2. Complex cultivation patterns
		2.4.3. Land principally occupied by agriculture with significant areas of natural vegetation
		2.4.4. Agro-forestry areas

3. Forests and semi-natural areas	3.1. Forests	3.1.1. Broad-leaved forest
		3.1.2. Coniferous forest
		3.1.3. Mixed forest
	3.2. Shrub and/or herbaceous vegetation associations	3.2.1. Natural grassland
		3.2.2. Moors and heathland
		3.2.3. Sclerophyllous vegetation
		3.2.4. Transitional woodland shrub
	3.3. Open spaces with little or no vegetation	3.3.1. Beaches, dunes, and sand plains
		3.3.2. Bare rock
		3.3.3. Sparsely vegetated areas
		3.3.4. Burnt areas
		3.3.5. Glaciers and perpetual snow
4. Wetlands	4.1. Inland wetlands	4.1.1. Inland marshes
		4.1.2. Peat bogs
	4.2. Coastal wetlands	4.2.1. Salt marshes
		4.2.2. Salines
		4.2.3. Intertidal flats
5. Water bodies	5.1. Continental waters	5.1.1. Water courses
		5.1.2. Water bodies
	5.2. Marine waters	5.2.1. Coastal lagoons
		5.2.2. Estuaries
		5.2.3. Sea and ocean

Source: http://ec.europa.eu/agriculture/publi/landscape/about.htm).

Alone, in the ruins of my mind,
On an island of reflection,
Deserted by all,
Except for rejection.

4

A pattern-oriented individual-based land-use-transition model: utility maximization at varying levels of complexity and rationality (CORA)

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Abstract

In this research we investigate whether real-world agricultural land-use systems can be meaningfully approximated by emergent—complex systems—behavior. We do so by constructing an innovative pattern-oriented individual-based land-use-transition model. The model can exhibit complex systems behavior by combining simple yet plausible temporal and spatial mechanisms. These can operate on cellular automata—abstractions of farmers—and allow automata to maximize utility at varying levels of complexity, rationality, and foresight. By calibrating agricultural benefits and costs to real-world relative perceptions, we analyze spectrums of landscapes in states of statistical equilibrium. Because—input—complexity is systematic, aggregate output is truly emergent. In particular, intensification of agriculture emerges. By systematically combining mechanisms we can construct different process-based filters generating different emergent behavior- and land-use patterns. Results suggest that real-world agricultural land-use systems can be meaningfully approximated by emergent—complex systems—behavior.

Keywords: land use; utility/preference; entropy/uncertainty; individual-based; complexity/emergence; self-organization; pattern formation.

4.1. Nomenclature

All non-variable matter is depicted upright. Scalar variables are italicized, vectors are italicized and barred while matrices are depicted bold upright. The temporal average of scalar variable x is defined as $<x>$. The term transition always refers to conversion of a particular land-use state into another, by an individual decision maker. The term entropy always refers to transition entropy, and the term equilibrium state(s) always refers to statistical-equilibrium state(s). Furthermore, the term iteration(s)—when used separately—always refers to (a) full model step(s), while the term step(s) always refers to iteration(s) of anticipation. The asterisk always indicates multiplication.

4.2. Introduction

A better understanding of land use is of major importance as it represents a vital link between human decision making and the natural environment (Young et al., 2006). Although the past few decades have allowed for successful attempts at modeling land use, e.g., CLUE (Veldkamp and Fresco, 1996), GLM (Aspinall, 2004), LUS (Loonen and Koomen, 2009), CGE models (Adams, 2005; Psaltopoulos et al., 2011), these models do not explicitly take into account decision-making processes at the individual level. This is due to input complexity of aggregate concepts, data and drivers typical for larger spatial scales (e.g., national, continental or global scale). Quantifying generalized verifiable relationships between—complex—individual decision making and aggregate land-use patterns is one of the major challenges for the next generation of land-use models (Parker et al., 2008a). Recently, more and more attempts have been made to view land-use systems as complex systems (Parker et al, 2003; Brown et al., 2008; Washington-Ottombre et al., 2010; Lopez-Carr et al., 2011), usually from the perspective of individual-based modeling (Jepsen et al., 2006; Parker et al, 2008b; Bao Le et al., 2010; Moreno et al., 2009; Wang et al., 2011; Lauf et al., 2011).

In this paper we investigate whether we can systematically approximate real-world complexity of agricultural land-use systems with emergent—complex systems— behavior (Strogatz, 2001; Liu et al., 2007). We do so by constructing a pattern-oriented (Grimm et al., 2005, 2006) individual-based land-use-transition model, written in NetLogo[2] (Centre for Connected Learning, 2011; Wilensky and Rand, 2011). The model generates emergent land-use patterns- and behavior resulting from the decisions of many individuals. It can exhibit

[2] NetLogo can be downloaded for free (Centre for Connected Learning 2011). The model may be obtained from corresponding author on request.

complex systems behavior (Strogatz, 2001; Liu et al., 2007) by combining simple yet plausible temporal and spatial mechanisms.

The model allows for maximization of individual utility at varying levels of complexity, rationality, and foresight. Because the model is individual-based it is unaffected by input complexity of aggregates, allowing us to systematically and reproducibly approximate real-world complexity.

Input complexity of real-world spatial distributions of land use would likely introduce disorganized complexity, i.e., input complexity beyond our ability to disentangle into reproducible systematic processes. We would then no longer be able to distinguish reproducible systematic emergent properties from emergent effects due to disorganized input complexity. Therefore, we do not introduce any real-world input complexity in this paper, although the model can work with real-world maps of land use.

4.3. Model

In this section we present an overview of land-use states, land-use-state transitions, and model structure- and mechanisms. Furthermore, we present a measure of aggregate uncertainty. Finally, we present initial land-use configuration and general form of model output. Thereafter, we will demonstrate and explain the effects of—combining—model mechanisms in detail in section 4.4.

4.3.1. *Land-use states*

Land can be in two states of agricultural land use, i.e., in a state of high-input- and in a state of low-input agriculture. High-input agricultural land is used more intensively than low-input land. Low-input agriculture causes soil-nutrient depletion while high-input agriculture results in increased sensitivity to diseases due to e.g., mono cultivation and sterilization of the soil. Conversely, high-input agriculture does not cause soil-nutrient depletion, while low-input agriculture does not cause increased sensitivity to diseases. Therefore, negative effects of low- and high-input land use may be assumed to be independent. Furthermore, land can be in a state of fallow land use by abandonment or by clearing of natural land, and it can be in a state of natural land use.

4.3.2. *Land-use-state transitions*

Individual decision makers are allowed to convert land to the fallow state by clearing of natural land or by abandonment of high- or low-input agricultural states. Individual decision makers are allowed to convert land to agriculture by taking fallow or natural land into production, associated with investment costs. Finally, decision makers can convert from high-input- to low-input agriculture and vice versa, associated with opportunity costs. That is, these costs are determined by what is lost by not remaining in a particular agricultural state. Regrowth of nature after clearing or abandonment is a gradual and natural process and not the result of a single iteration of decision making. Therefore, land can only be in a state of natural land because it remained in that state, or land remained in the fallow state sufficiently long for nature to regrow (fallowing).

4.3.3. *Structure*

In total, 10,000 cellular automata are placed in a fixed two-dimensional grid. Individual choices of automata are codetermined by economic preferences. Economic preferences are determined by perceived benefits—land-use-state utilities—and transition costs (Table 1). The costs of converting land from natural- or fallow states to high- or low-input states are made to weigh five and three times as much as perceived benefits, respectively. This models the usually high investment costs, compared to benefits from agriculture. Investment costs are even higher for high-input agriculture, compared to low-input agriculture. Based on utilities and transition costs, a stochastic utility-maximization mechanism (Fig. 1) determines individual choices. How stochastic this mechanism operates is determined by individual rationality. Rationality can be regulated in between extremes of—purely stochastic—irrational decision making and—purely deterministic—rational decision making. The more rational automata become, the more utility-maximizing decisions will occur. That is, rationality determines the strength of the effect of economic preferences on decision making. The occurrence of non-utility-maximizing decisions reflects that individuals also have non-economic preferences. An anticipation mechanism (Fig. 1) allows automata to project and compare utility gained from the possible different decision chains, departing from their present land-use state up to an arbitrary number of steps into the future. They then base present decisions on these future projections. Furthermore, effects of high- and low-input agriculture are modeled by independent utility-feedback mechanisms (Fig. 1) that operate on automata in high- and low-input states, respectively. Finally, more efficient sharing of costs by larger groups of automata is modeled by a co-operation mechanism (Fig. 1). This mechanism causes transition costs into agricultural states to decrease, proportional to the count of neighboring agricultural states. Note that only the utility-maximization mechanism allows for actual decision making; all other mechanisms only affect decision making indirectly by manipulating its inputs (Fig. 1).

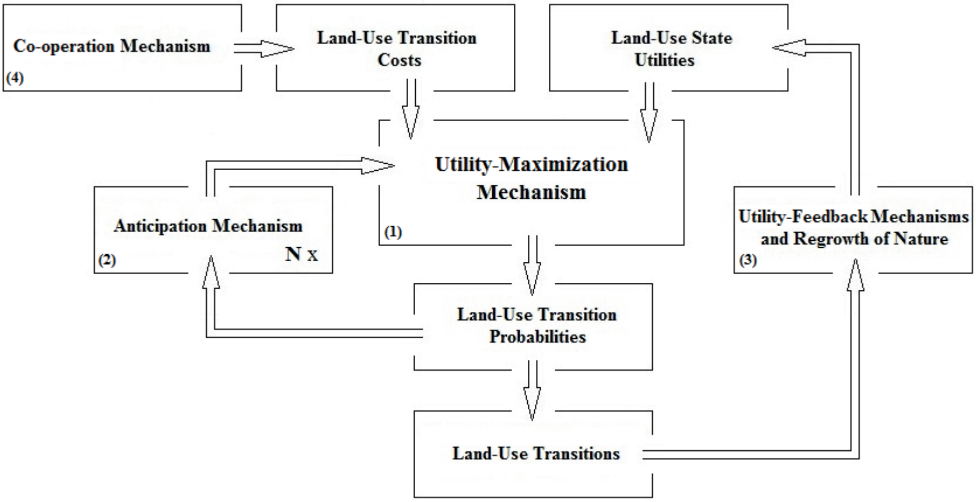

Fig. 1. Flowchart of CORA.

Note: Mechanisms are specified by their order of introduction in the next section. This also specifies the order of level of complexity. The utility-maximization mechanism (1) is the core of the model and will be introduced first. The model is named CORA, because we attempt to model real-world complexity of agricultural land-use systems at varying levels of—CO—complexity and—RA—rationality.

4.3.4. *Aggregate uncertainty*

The stochastic nature of individual decision making together with the large number of decision makers, make it meaningful to compute the entropy over land-use transitions. We know land-use states, possible transitions, and transition probabilities for each automaton at any time. Therefore, the real-time entropy over land-use transitions or transition entropy $\Omega_T(t)$ may be defined as follows:

$$\Omega_T(t) \equiv -\sum_{i=1}^{N}\sum_{T} p_T(t)\ln(p_T(t)) \tag{1}$$

Equation (1) summates individual expectation values of transition uncertainty, over all N individual automata. Individual expectation values are computed over possible transitions T and their transition probabilities $p_T(t)$ for each individual automaton at time t. The base of logarithm used is mathematically arbitrary, as we can convert to any other base larger than zero and unequal to one by multiplication of a constant. Transition entropy $\Omega_T(t)$ provides us with a quantitative measure of aggregate uncertainty. This will prove very useful when comparing and interpreting results, because model output depends strongly on systematic manipulation of aggregate uncertainty.

4.3.5. ***Model output***

Model output strongly depends on initial land use. Therefore, we assign equal values of 33 %—of total land use—to initial high-input-, low-input- and fallow land use throughout this paper for reasons of comparison. Initial natural land use is always set to zero. Furthermore, the model produces spectrums of statistical-equilibrium states. These statistical-equilibrium states are approximated by computation of temporal averages over finite iterations. Although statistical-equilibrium states are approximated by only 500 iterations, this approximation is sufficiently close as temporal averages no longer noticeably change when number of iterations is increased further (not shown). Hence, time does not play a role in our analysis of produced spectrums of equilibrium states.

4.4. Temporal and spatial mechanisms

The model is built up out of mechanisms that can affect each automaton independently and simultaneously, thereby affecting the aggregate system. Any mechanism operating on N automata of which the outcome is determined by precisely these N automata, is defined as a temporal mechanism. This simply quantifies that a temporal mechanism does not introduce any spatial dependency, i.e., an automaton operated upon is not affected by any other automata. Any mechanism operating on N automata of which the outcome is affected by a number of automata greater than N, is defined as a spatial mechanism. This simply quantifies that such a mechanism does introduce spatial dependency, i.e., an automaton operated upon is affected by at least one other automaton. Finally, note that for reasons of clarity—which will become apparent later—model results are not shown until after subsection 4.4.1.1.

4.4.1. ***Temporal mechanisms***

4.4.1.1. *Utility maximization*

Although we may accurately describe decision making for some fraction of the population, human behavior can never be entirely captured by a set of rational rules. There are always those who take irrational decisions, i.e., for other reasons than maximizing personal gain. The utility-maximization mechanism attempts to take this into account by introducing individual uncertainty in a systematic way. That is, the probability that automata will make rational decisions can be regulated by systematic manipulation of individual uncertainty. This systematic manipulation can be measured by using transition entropy Ω_T (*4.3.4. Aggregate* *uncertainty*). Because individual uncertainty is directly related to entropy, there is a direct relationship between entropy and occurrence of utility maximization. The utility-maximization mechanism—and it alone—allows for actual decision making. All other mechanisms simply manipulate the input of the utility-maximization mechanism (Fig. 1).

Automata individually determine which decision would maximize their utility by comparing the net utility that would be gained by remaining in their present land-use state, to the net utility that would be gained by making the transition into any of the other possible land-use states. The likelihood of a transition into a different state is determined by the difference between land-use-state utilities and by the costs of that transition. The more positive the land-use-state utility difference between states, the greater the likelihood of that transition. Similarly, the smaller the associated transition costs, the greater the likelihood of that transition. If the present land-use state already yields maximum net gain in utility, the option with the greatest likelihood is to remain in that state. In that case transition costs are zero. Below, the utility-maximization mechanism is demonstrated in detail. First, we describe the possible transitions by defining a transition-probability matrix:

$$\begin{array}{cc} & \begin{array}{cccc} I & A & N & F \end{array} \\ \mathbf{P} \equiv & \begin{pmatrix} [1-(p_{IF}+p_{IA})] & p_{IA} & 0 & p_{IF} \\ p_{AI} & [1-(p_{AF}+p_{AI})] & 0 & p_{AF} \\ p_{NI} & p_{NA} & [1-(p_{NF}+p_{NA}+p_{NI})] & p_{NF} \\ p_{FI} & p_{FA} & 0 & [1-(p_{FA}+p_{FI})] \end{pmatrix} \begin{array}{c} I \\ A \\ N \\ F \end{array} \end{array} . \quad (2)$$

From the first two columns of equation (2), we see that automata can go to high-input state *I* or low-input state *A* by making the transition from fallow land *F*, by making the transition directly from natural land *N*, or by making the transition from *I* to *A* (or vice versa). From the fourth column of equation (2), we see that automata can go to the fallow state *F*, either by clearing natural land *N* or by making the transition from one of the agricultural states *I* or *A*. The transitions in the first, second and fourth column of equation (2) are realistic. Transitions in the third column of equation (2), from *A, I* and *F* to *N* are considered unrealistic. That is, these transitions cannot occur because regrowth of nature is a gradual and natural process and not the result of a single decision. Therefore, the mechanism of regrowth of nature is treated externally to decision-making (*4.1.3. Utility feedbacks and regrowth of nature*).
All land-use states are assigned a land-use-state utility value and all transitions are assigned a transition cost (Table 1). In equation (2), the transition-probability element $p_{ij} \in \mathbf{P}$—numeric indices—for a transition from present state i—row—to future state j—column—is defined as:

$$p_{ij} = \frac{e^{\beta(U_j - U_i - C_{ij})}}{\sum_{j=1}^{m} e^{\beta(U_j - U_i - C_{ij})}} \tag{3}$$

In equation (3), $m = 4$ as $\mathbf{P}$ is a four by four matrix, U_j is land-use-state utility of future state j, and U_i is land-use-state utility of present state i. Transition costs associated with a transition from present state i to future state j are expressed by the $C_{ij} \geq 0, \forall i, j$. Net gain from making a transition is equal to $(U_j - C_{ij})$ which may be negative as well. If no transition is made, net gain is equal to U_i. Note that if $i = j$ then $C_{ij} = 0$, that the p_{ij} in equation (3) are used in the entropy Ω_T in equation (1) and that $\sum_{j=1}^{m} p_{ij} = 1, \forall i$. The parameter $\beta \in [0, \infty)$ regulates rationality of individual behavior (*3.3. Structure*). For $\beta = 0$, utility maximization cannot occur because automata then behave purely stochastic, i.e., irrational. The entropy is then maximal, which corresponds to minimal occurrence of utility maximization. For $\beta \to \infty$, automata will behave purely deterministic. Automata are then maximally rational and only make utility-maximizing decisions (with probability one). The entropy is then minimal (zero), which corresponds to maximal occurrence of utility maximization.

Table 1. Relative perceptions of benefits—land-use-state utilities—(U) and transition costs (C).

$I\ (U_I = 10)$	$A\ (U_A = 8)$	$N\ (U_N = 2)$	$F\ (U_F = 4)$	
$(C_{II} = 0)$	$(C_{IA} = 10)$	-	$(C_{IF} = 0)$	*I*
$(C_{AI} = 8)$	$(C_{AA} = 0)$	-	$(C_{AF} = 0)$	*A*
$(C_{NI} = 9.6)$	$(C_{NA} = 7.1)$	$(C_{NN} = 0)$	$(C_{NF} = 2)$	*N*
$(C_{FI} = 7.6)$	$(C_{FA} = 5.1)$	-	$(C_{FF} = 0)$	*F*

Note: The first row contains land-use-state utilities. Transition costs should be read from row to column. Empty table entries correspond to non-occurring transitions. *I* is high-input land use, *A* is low-input land use, *N* is natural land use and *F* is fallow land use.

In Table 1, $U_I > U_A$ because high-input agriculture is more beneficial than low-input agriculture. However, transition costs into high-input agriculture are proportionately higher than for low-input agriculture. Moreover, high- and low-input states *I* and *A* can be cultivated persistently with net benefits U_I and U_A, respectively. We set clearing costs $C_{NF} \equiv U_F - U_N$ to specify that the transition from *N* to *F* is not used to derive benefit from e.g., harvesting of trees. It ensures that net benefit from this transition is always perceived to be zero, preventing its occurrence for economic reasons. Because transition costs $C_{ij} \geq 0, \forall i, j$, and clearing costs cannot be zero, we must have that $U_F > U_N$. The actual difference is arbitrary, as long as $(U_N < U_F) < (U_A < U_I)$, ensuring that agriculture is always the dominant source of economic benefit. Because transition costs weigh exponentially in equation (3), $C_{NI} = (U_I - U_N) + \ln(5)$ and ,$C_{FI} = (U_I - U_F) + \ln(5)$ to make costs of converting land from natural- or fallow states to high-input state weigh five times as much as perceived benefits, in decision making (*3.3. Structure*). Furthermore, $C_{NA} = (U_A - U_N) + \ln(3)$ and $C_{FA} = (U_A - U_F) + \ln(3)$ to make costs of converting land from natural- or fallow states to low-input state weigh three times as much as perceived benefits, in decision making. Finally, it is always true that $C_{NI} = C_{NF} + C_{FI}$ and $C_{NA} = C_{NF} + C_{FA}$.

4.4.1.2. *Anticipation*

To enable automata to make decisions informed by their expectations of future consequences of present decisions, automata can compute net total expectation values of utility over an arbitrary number of steps into the future, given their present land-use state. This mechanism is explained in detail below. First, we show how automata compute expectation values of utility gained from land use after the first step ($n = 1$):

$$\overline{U}(1) = \mathbf{M}(0)\ \overline{U}(0) \quad \text{, in which } \mathbf{M}(0) \text{ is} \tag{4}$$

$$\mathbf{M}(0) = \begin{pmatrix} [1-(p_{IF}(0)+p_{IA}(0))] & p_{IA}(0)(1-\frac{C_{IA}}{U_A(0)}) & 0 & p_{IF}(0)(1-\frac{C_{IF}}{U_F(0)}) \\ p_{AI}(0)(1-\frac{C_{AI}}{U_I(0)}) & [1-(p_{AF}(0)+p_{AI}(0))] & 0 & p_{AF}(0)(1-\frac{C_{AF}}{U_F(0)}) \\ p_{NI}(0)(1-\frac{C_{NI}}{U_I(0)}) & p_{NA}(0)(1-\frac{C_{NA}}{U_A(0)}) & [1-(p_{NF}(0)+p_{NA}(0)+p_{NI}(0))] & p_{NF}(0)(1-\frac{C_{NF}}{U_F(0)}) \\ p_{FI}(0)(1-\frac{C_{FI}}{U_I(0)}) & p_{FA}(0)(1-\frac{C_{FA}}{U_A(0)}) & 0 & [1-(p_{FA}(0)+p_{FI}(0))] \end{pmatrix}, \tag{5}$$

and $\overline{U}(0) = (U_I(0) \quad U_A(0) \quad U_N(0) \quad U_F(0))^T$ is the column-vector of land-use-state utilities of high-input land use *I*, low-input land use *A*, natural land use *N* and fallow land use *F* (Table 1). In equation (5) we see transition probabilities, transition costs, and land-use-state utilities as defined in equation (3). However, expectation values of utility must be used to re-compute transition probabilities after each step. This is to ensure that automata use all information available to them in the present while anticipating on future consequences of decisions. This explains why transition probabilities are no longer constant in equation (5). Note that rationality parameter β is also present in equation (5), in the transition probabilities.

Furthermore, that if transition costs are zero, $\mathbf{M}(0)$ reduces to the transition-probability matrix $\mathbf{P}(0)$, equal to matrix $\mathbf{P}$ in equation (2). In general, $\mathbf{M}(n)$ reduces to $\mathbf{P}(n)$ for zero transition costs. The matrix $\mathbf{M}(n)$ cannot be interpreted as a transition-probability matrix itself. Hence, it is a more general transition matrix. Gains in utility after n steps, resulting from the different states after $n-1$ steps, are computed by a linear recursive transformation through the more general transition matrix $\mathbf{M}(n)$:

$$\overline{U}\ (n) = \mathbf{M}(n-1)\ \overline{U}\ (n-1) \tag{6}$$

4

Therefore, the utility expected to be gained in going from state $n-1$ to state n will be:

$$\overline{U}\ (n) = \mathbf{M}(n-1)\overline{U}\ (n-1) = \mathbf{M}(n-1)\mathbf{M}(n-2)\cdots\mathbf{M}(0)\overline{U}\ (0) \ = \left(\prod_{k=1}^{n}\mathbf{M}(n-k)\right)\overline{U}\ (0)$$

(7)

Economics of temporal discounting state that the expected utility from a decision in the present should be higher than the expected utility from the same decision but projected to be made in the (near) future (Ebert 2010). Therefore, stationary discounting is applied by defining anticipation parameter $\omega \equiv \frac{1}{1+r}$ with discount rate $r \in [0,\infty)$. This ensures that expected utility from decisions decreases monotonously compared to when the same decisions would be made earlier. The parameter has a range of $\omega \in [0,1]$ and is applied to equation (4) by multiplication with ω, yielding discounted expected utility. Discounted expected utility is assigned the symbol V, resulting in the following matrix notation:

$$\overline{V}\ (1) = \omega\mathbf{M}(0)\overline{U}\ (0)\ \ ,\ \overline{V}(0) = \overline{U}(0) \tag{8}$$

We can now compute the discounted expected utility at n steps into the future, using equation (6):

$$\overline{V}\ (n) = \omega^n\mathbf{M}(n-1)\mathbf{M}(n-2)\cdots\mathbf{M}(0)\overline{V}\ (0) \ = \omega^n\left(\prod_{k=1}^{n}\mathbf{M}(n-k)\right)\overline{V}\ (0), \tag{9}$$

$$\text{equal to } \overline{V}\ (n) = \omega^n\overline{U}\ (n), \text{ as } \overline{V}(0) = \overline{U}(0). \tag{10}$$

At this point, automata—farmers—would want to know which land-use state will allow them to gain a maximum of discounted expected utility, in total after n steps. To this purpose, automata must compute total discounted expected utility gains:

$$\overline{V}(n) = \sum_{i=0}^{n}\overline{V}(i) = \sum_{i=0}^{n}\omega^i\left(\prod_{k=1}^{i}\mathbf{M}(i-k)\right)\overline{V}(0) = \sum_{i=0}^{n}\omega^i\,\overline{U}(i) \tag{11}$$

To compute $\overline{V}(n)$ in equation (11), automata compute new transition probabilities after each step. For the first step, transition probabilities $p_{ij}(0)$ simply follow from $\overline{V}(0)$ using equation (11) and then equation (3). These probabilities are then used to compute $\overline{U}(1)$. It is then possible to compute $\overline{V}(1)$ from equation (11):

$$\overline{V}(1) = \sum_{i=0}^{1} \omega^i \overline{U}(i) = \overline{U}(0) + \omega \overline{U}(1). \tag{12}$$

The transition probabilities $p_{ij}(1)$ for the second step then follow from applying equation (3) to the entries of $\overline{V}(1)$ in equation (12). From these probabilities we may compute $\overline{U}(2)$, which may be used to compute $\overline{V}(2)$, thus allowing us to compute transition probabilities $p_{ij}(2)$ for the third step etc., recursively calculating $\overline{V}(n)$ in equation (11). Once $\overline{V}(n)$ is known, automata make an actual decision based on the updated transition probabilities $p_{ij}(n)$, by applying the entries of $\overline{V}(n)$ to their present situation by using equation (3) again. Transition costs remain constant during this process.

As can be seen from equation (6) any future state after step n depends on the previous state at after step $n-1$ only. Therefore, the sequence of discounted expected utility vectors $\{\omega^i \overline{U}(i)\}$ resulting from equation (11) constitutes a Markov chain counting $n+1$ elements. Thus n in equation (11) determines the length of the decision chain, i.e., how many steps automata can see into the future, while anticipation parameter ω regulates the effect of discounting. If $\omega \to 0$, i.e., discount rate $r \to \infty$, expectation values from future decisions will be negligible. In this case, decisions are effectively a result of comparing present utility values only, i.e., all other values in equation (11) are zero. If $\omega \to 1$, i.e., discount rate $r \to 0$, expectation values from future decisions will not be negligible and will affect decision making. In this case, decisions are a result of comparing non-zero discounted expected total utility value entries of equation (14).
Below, the utility-maximization mechanism and effects of rationality parameter β and anticipation parameter ω are demonstrated together (Fig. 2). Note that agricultural marginal utility is the total rate of change of utility from high- and low-input states. That is, it is the sum of all individual utility increments/decrements due to agriculture, per iteration. To arrive at agricultural marginal utility per automaton U_{Ma}, we divided agricultural marginal utility by the total number of automata. Rationality $\beta \in [0,2.5]$ was sampled using increments of 1/10. Statistical-equilibrium states of transition entropy Ω_T, agricultural marginal utility per automaton U_{Ma} and land use were then approximated by 500 iterations for each sample-point, both with $(\omega = 0.25)$ and without $(\omega = 0)$ anticipation (Fig. 2). Note that if we set anticipation parameter $\omega = 0 (\Leftrightarrow r \to \infty)$, the model reduces to its previous form

(*4.4.1.1. Utility maximization*). This explains our choice of presenting results of this- and the previous subsection together.

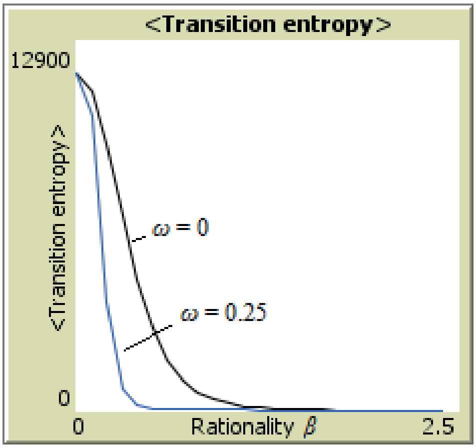

Fig. 2a. Statistical-equilibrium states—approximated by 500 iterations—of transition entropy Ω_T plotted against rationality β without and with anticipation, i.e., for $\omega = 0$ (black) and $\omega = 0.25$ (blue), respectively.

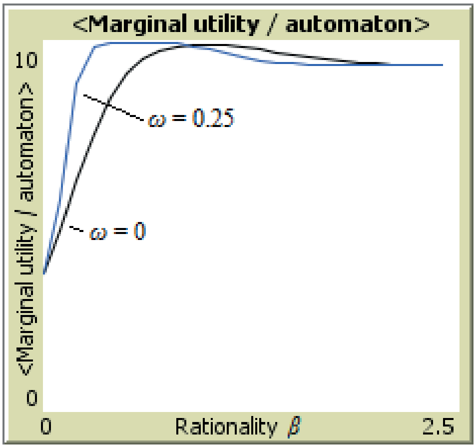

Fig. 2b. Statistical-equilibrium states—approximated by 500 iterations—of agricultural marginal utility U_{Ma} plotted against rationality β without and with anticipation, i.e., for $\omega = 0$ (black) and $\omega = 0.25$ (blue), respectively.

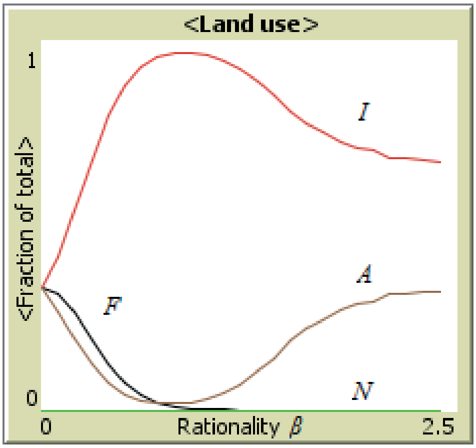

Fig. 2c. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I, A, N* and *F* plotted against rationality β without anticipation, i.e., for $\omega = 0$

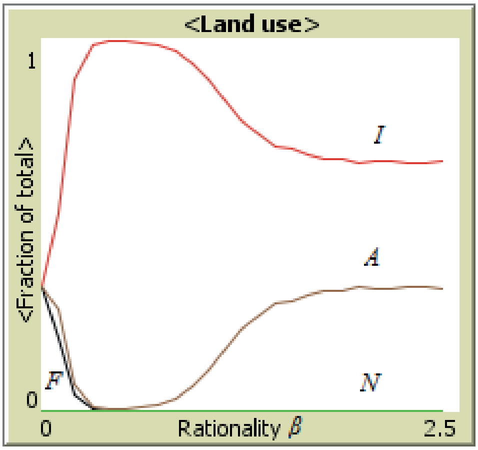

Fig. 2d. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I, A, N* and *F* plotted against rationality β with anticipation, i.e., for $\omega = 0.25$

Note: Length of Markov chain $n = 10$. Red is high-input fraction *I* of total land use, brown is low-input fraction *A* of total land use, green is natural fraction *N* of total land use, black is fallow fraction *F* of total land use. Total land use is $I + A + N + F = 1, \forall t$.

Table 2. Statistical-equilibrium states—approximated by 500 iterations—of entropies Ω_T, marginal utilities U_{Ma} and land-use fractions *I*, *A*, *N* and *F*.

(β,ω)	$<\Omega_T>$	$<U_{Ma}>$	$<I>$	$<A>$	$<N>$	$<F>$
$(0,x)$	11,755.2	3.7	0.33	0.33	0	0.33
$(1,0)$	245	9.9	0.99	0	0	0.01
(2.5,0)	4.4	9.4	0.68	0.32	0	0
$(1,0.25)$	41.1	9.8	0.89	0.11	0	0
(2.5,0.25)	0.1	9.3	0.67	0.33	0	0

Note: Length of Markov chain $n=10$. *I* is high-input fraction of total land use, *A* is low-input fraction of total land use, *N* is natural fraction of total land use and *F* is fallow fraction of total land use. Total land use is $I+A+N+F=1,\forall t$. The $x\in(0,x)$ indicates that ω has no effect for $\beta=0$.

For $\beta=0$ (Table 2), transition probabilities are always uniformly distributed, which corresponds to a maximal entropy and uniformly distributed land uses. For the utility-maximization mechanism without anticipation high-input agriculture approaches its maximum together with agricultural marginal utility around $\beta=0.86$ (Fig. 2c). This occurs around $\beta=0.47$ for the utility-maximization mechanism with anticipation (Fig. 2d). Until these values, increasing high-input agriculture (Fig. 2c–2d) coincides with decreasing entropy (Fig. 2a). This coincides with increasing agricultural marginal utility (Fig. 2b), without and with anticipation, respectively. This is reflected by curves becoming steeper with anticipation (Fig. 2, Table 2). Furthermore, without anticipation land use becomes stable around $\beta=2$ (Fig. 2c). With anticipation, land use already becomes stable around $\beta=1.5$ (Fig. 2d). Furthermore, we observe spectrums of statistical-equilibrium states for which agricultural marginal utility is stable, for $\beta=0.86$ (Fig. 2c) and $\beta=0.47$ (Fig. 2d) without and with anticipation, respectively. Finally, natural land use *N* is always zero because regrowth of nature does not yet occur (Fig. 2c–2d, Table 2).

Fig. 3a. Landscape after 500 iterations for rationality $\beta = 1$ with anticipation $\omega = 0$

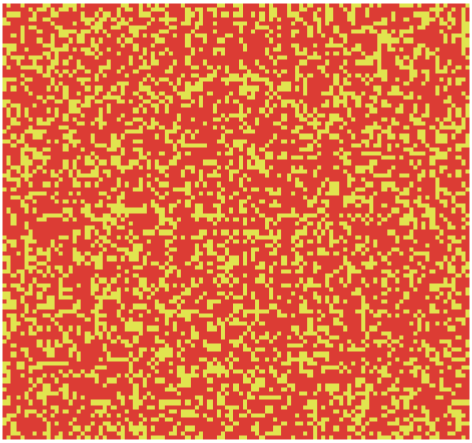

Fig. 3b. Landscape after 500 iterations for rationality $\beta = 2.5$ with anticipation $\omega = 0$

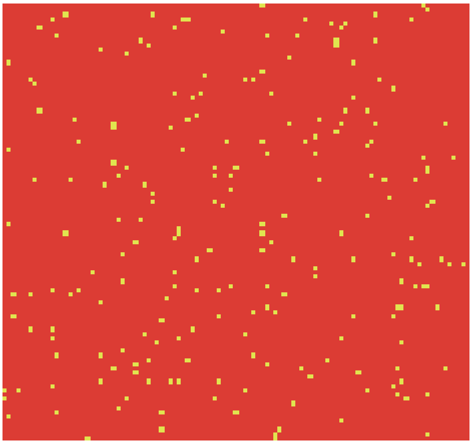

Fig. 3c. Landscape after 500 iterations for rationality $\beta = 1$ with anticipation $\omega = 0.25$

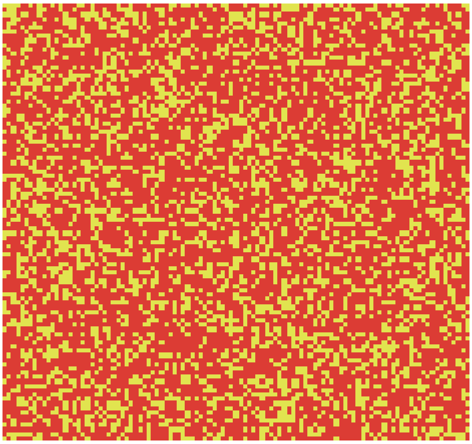

Fig. 3d. Landscape after 500 iterations for rationality $\beta = 2.5$ with anticipation $\omega = 0.25$

Note: Red is high-input fraction *I* of total land use, yellow is low-input fraction *A* of total land use, green is natural fraction *N* of total land use, black is fallow fraction *F* of total land use. Total land use is $I + A + N + F = 1, \forall t$.

Because the utility-maximization mechanism is temporal and not spatial (*4.4. Temporal and spatial mechanisms*), automata behave spatially independent. Furthermore, landscapes are quite similar, comparing with (Figs. 3c–3d) and without (Figs. 3a–3b) anticipation. Moreover, differences between landscapes become even smaller for increasing β with fixed ω (Table 2). Comparing Fig. 2 and Fig. 3, the need for studying statistical-equilibrium states is evident.

4.4.1.3. *Utility feedbacks and regrowth of nature*

Utility-feedback mechanisms affect decision making indirectly by manipulation of inputs of the utility-maximization mechanism (Fig. 1), and are modeled according to (*4.3.1. Land-use states*). A negative effect of low-input agriculture is that soil nutrients will become depleted over time. This is modeled by decreasing the low-input agriculture utility as long as land use remains low input agriculture. This causes low-input agricultural land to become fallow with increasing probability over time, as the utility associated with the low-input state gradually declines and drops below that associated with the fallow state. Furthermore, fallow land that has been in a low-input state for a number of iterations before becoming fallow is allowed to recover. This is accomplished by increasing the low-input agriculture utility again after each iteration as long as land use remains fallow, increasing the probability of becoming low input again. Furthermore, negative effects of high-input agriculture and recovery therefrom, are also modeled by two such mechanisms. That is, independent from the soil-nutrient depletion- and recovery mechanisms. Consequently, when high-input land use has been practiced too long at the same location automata are forced to switch back to low-input- or fallow land use. Land that remains in fallow state sufficiently long, will turn into nature. Because regrowth of nature is considered an independent process external to decision making, it can only occur by an independent stochastic mechanism. This mechanism causes the transition from fallow land to natural land to occur once in every five iterations on average. The rate of decrease of land-use-state utility is assumed to be 25 % lower for high-input agriculture compared to low-input agriculture, to model that high-input agriculture is usually more productive for a longer time. Rates of increase of land-use-state utility, i.e., recovery rates, are assumed to be equal. All rates are illustrative, i.e., they are not calibrated to concrete data. Rates are regulated by one parameter ε, which is then internally manipulated. Low-input agriculture utility decreases by units of ε, high-input agriculture utility decreases by units of.$0.75 * \varepsilon$ Both utilities are increased by units of ε in case of recovery. The parameter ε has been chosen to create noticeable yet comprehensible effects, allowing to compare with earlier model forms.

Below, the effects of adding utility feedbacks and the regrowth of nature mechanism in addition to effects of rationality parameter β and anticipation parameter ω are demonstrated (Fig. 4). Rationality $\beta \in [0,2.5]$ was sampled using increments of 1/10. Statistical-equilibrium states of transition entropy Ω_T, agricultural marginal utility per automaton U_{Ma} and land use were then approximated by 500 iterations for each sample-point, both with $(\omega = 0.25)$ and without $(\omega = 0)$ anticipation (Fig. 4). Note that if we set parameter $\varepsilon = 0$, the model reduces to its previous form (*4.4.1.2. Anticipation*). Furthermore, that agricultural land-use-state utilities (Table 1) are no longer constant.

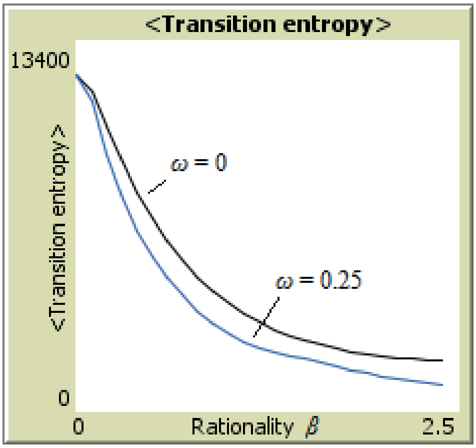

Fig. 4a. Statistical-equilibrium states—approximated by 500 iterations—of transition entropy Ω_T plotted against rationality β without and with anticipation, i.e., for $\omega = 0$ (black) and $\omega = 0.25$ (blue), respectively.

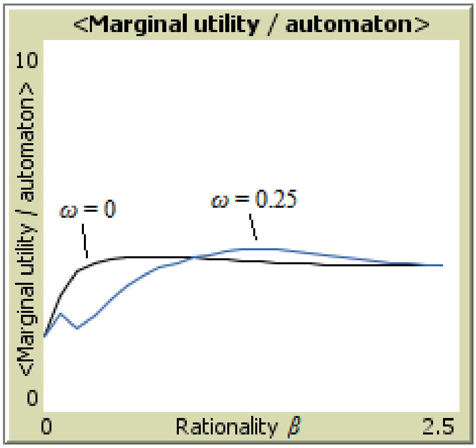

Fig. 4b. Statistical-equilibrium states—approximated by 500 iterations—of agricultural marginal utility U_{Ma} plotted against rationality β without and with anticipation, i.e., for $\omega = 0$ (black) and $\omega = 0.25$ (blue), respectively.

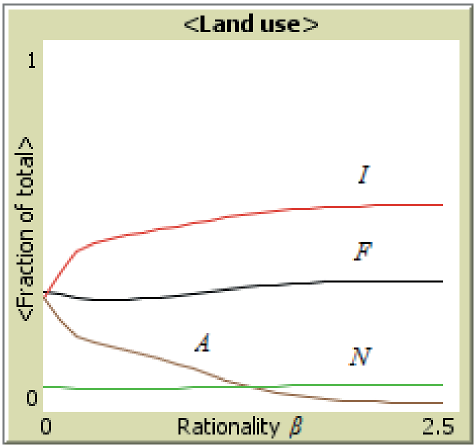

Fig. 4c. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I, A, N* and *F* plotted against rationality β without anticipation, i.e., for $\omega = 0$

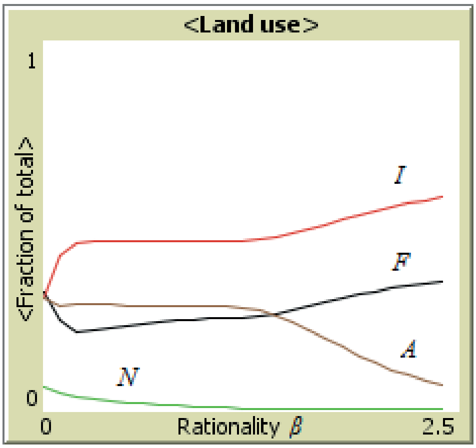

Fig. 4d. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I, A, N* and *F* plotted against rationality β with anticipation, i.e., for $\omega = 0.25$

Note: Length of Markov chain $n = 10$ and feedback parameter $\varepsilon = 0.1$. Red is high-input fraction *I* of total land use, brown is low-input fraction *A* of total land use, green is natural fraction *N* of total land use, black is fallow fraction *F* of total land use. Total land use is $I + A + N + F = 1, \forall t$.

Table 3. Statistical-equilibrium states—approximated by 500 iterations—of entropies Ω_T, marginal utilities U_{Ma} and land-use fractions *I*, *A*, *N* and *F*.

(β,ω)	$<\Omega_T>$	$<U_{Ma}>$	$<I>$	$<A>$	$<N>$	$<F>$
$(0,x)$	12,151.3	3.4	0.31	0.31	0.06	0.32
$(1,0)$	3915.4	4.9	0.52	0.09	0.07	0.32
$(2.5,0)$	1804.8	4.7	0.57	0	0.07	0.36
$(1,0.25)$	2681.8	4.8	0.46	0.28	0.01	0.25
$(2.5,0.25)$	903.2	4.6	0.59	0.05	0	0.36

Note: Length of Markov chain $n=10$ and feedback parameter $\varepsilon=0.1$. *I* is high-input fraction of total use, *A* is low-input fraction of total land use, *N* is natural fraction of total land use and *F* is fallow fraction of total land use. Total land use is $I+A+N+F=1,\forall t$. The $x\in(0,x)$ indicates that ω has no effect for $\beta=0$.

Results for the $\beta=0$ model (Table 2) are slightly offset compared to Table 3, as entropy is higher after introduction of the regrowth of nature mechanism, although not because of utility maximization. This mechanism simply causes a more uniform distribution of land uses, explaining the increase in entropy (Tables 2–3). The decrease in agricultural marginal utility (Tables 2–3) can be explained by the specification of U_N (Table 1). That is, it might just as well have been an increase for a higher specific value of U_N. For the utility-maximization mechanism affected by feedback mechanisms without anticipation (Fig. 4c, Table 3), we see increasing high-input- and fallow land use at the expense of low-input agriculture for increasing rationality, while natural land use does not change much. For the utility-maximization mechanism affected by feedback mechanisms with anticipation (Fig. 4d), we see stable high- and low-input agriculture until around $\beta=1.25$. For $\beta=1.25$, high-input agriculture suddenly strongly increases at the expense of low-input agriculture. Fallow land shows an overall increase at the expense of natural land use (for $\beta=1.25$) and low-input land use (for $\beta=1.25$). The entropy with anticipation (Fig. 4a, blue) is still lower than the one without anticipation (Fig. 4a, black). Apparently there is a higher occurrence of individual utility maximization with anticipation. Remarkably, the agricultural marginal utility with anticipation (Fig. 4b, blue) remains lower than the one without anticipation (Fig. 4b, black) until around $\beta=1$. The agricultural marginal utility without anticipation (Fig. 4b, black) stabilizes almost immediately, around $\beta=0.3$, while the one with anticipation (Fig. 4b, blue) stabilizes around $\beta = 1.25$. Just as for the previous model form (*4.4.1.2. Anticipation*), we observe spectrums of statistical-equilibrium states for which agricultural marginal utility is stable, for $\beta > 0.3$ (Fig. 4c) and $\beta = 1.25$ (Fig. 4d) without and with anticipation, respectively. Because land use and land-use transitions determine increments or decrements of agricultural marginal utility, observed land uses produce these nearly constant agricultural marginal utilities together. That is, for $\beta > 0.3$ (Fig. 4c) and $\beta = 1.25$ (Fig. 4d).

Because the added utility-feedback mechanisms are temporal and not spatial (*4.4. Temporal and spatial mechanisms*), automata still behave independently. Furthermore, after introducing utility-feedback mechanisms each automaton in the landscapes in Fig. 5 makes independent land-use transition cycles. Whereas before automata could remain in the same state indefinitely (Fig. 3, Table 2). Upon increasing rationality from $\beta = 1$ (Fig. 5a, Fig. 5c) to $\beta = 2.5$ (Fig. 5b, Fig. 5d), high-input agriculture increases and low-input agriculture strongly decreases (Table 3), both with (Figs. 5c–5d) and without (Figs. 5a–5b) anticipation. Upon enabling automata to anticipate for $\beta = 1$ (Fig. 5a, Fig. 5c), natural- and high-input land use decrease and low-input agriculture strongly increases (Table 3), compared to without anticipation (Fig. 5a). Finally, upon enabling automata to anticipate for $\beta = 2.5$ (Fig. 5b, Fig. 5d), natural land use decreases and low-input agriculture increases (Table 3), compared to without anticipation (Fig. 5b).

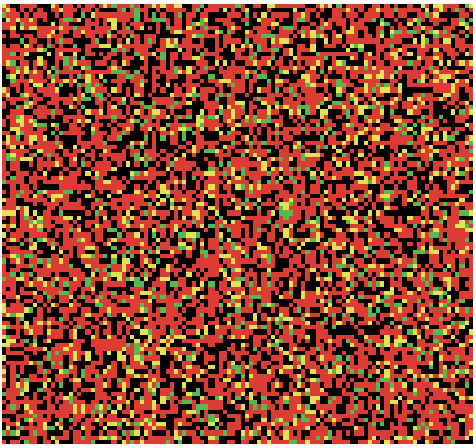

Fig. 5a. Landscape after 500 iterations for rationality $\beta = 1$ with anticipation $\omega = 0$

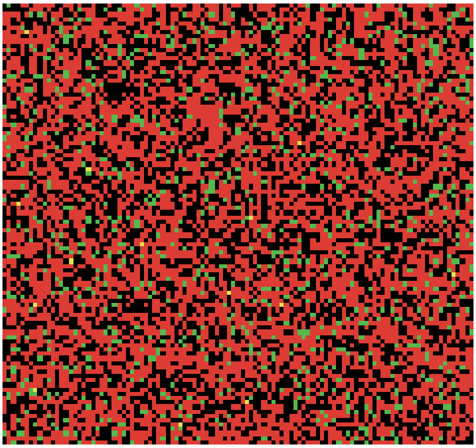

Fig. 5b. Landscape after 500 iterations for rationality $\beta = 2.5$ with anticipation $\omega = 0$

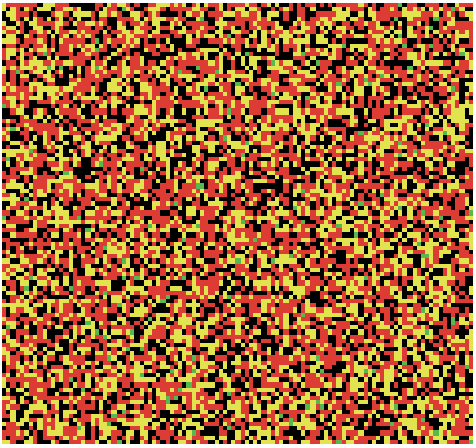

Fig. 5c. Landscape after 500 iterations for rationality $\beta = 1$ with anticipation $\omega = 0.25$

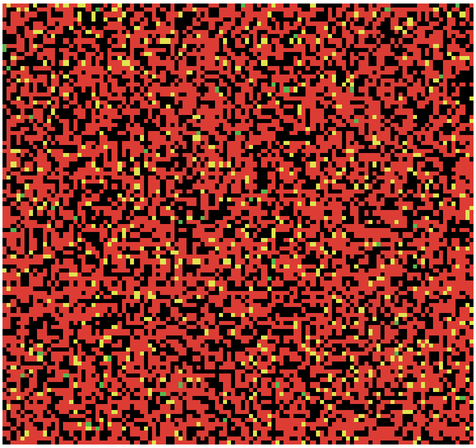

Fig. 5d. Landscape after 500 iterations for rationality $\beta = 2.5$ with anticipation $\omega = 0.25$

Note: Red is high-input fraction *I* of total land use, yellow is low-input fraction *A* of total land use, green is natural fraction *N* of total land use, black is fallow fraction *F* of total land use. Total land use is $I + A + N + F = 1, \forall t$.

4.4.2. ***Spatial mechanisms***

4.4.2.1. *Co-operation*

Larger groups of farmers often share costs more efficiently, e.g., by forming agricultural co-operatives. To simulate this, automata use a near neighbor mechanism (Hofbauer and Sigmund 2003). They scan the land-use state of their eight nearest neighbors for each iteration. For every neighboring automaton in a low- or high-input agricultural state, the costs of making the transition from fallow land to that agricultural state decrease proportionally. Thus, the more neighboring automata in a high- or low-input agriculture state, the higher the probability that near automata in non-agricultural states will start practicing agriculture as well. Note that this is a spatial mechanism (*4.4. Temporal and spatial mechanisms*) that manipulates the inputs of the utility-maximization mechanism. The more rational automata become, the more the effects of co-operation become apparent. The economic advantage for automata gained from co-operation can be regulated with parameter δ. That is, transition costs into high- and low-input states decrease by a factor of δ multiplied with the count of neighboring automata in high- and low-input agriculture states, respectively. Co-operation parameter δ has been chosen such to create noticeable yet comprehensible effects, allowing to compare with earlier model forms.

Below, the effect of adding the co-operation mechanism and effects of rationality parameter β and anticipation parameter ω are demonstrated together (Fig. 6). Rationality $\beta \in [0,2.5]$ was again sampled using increments of 1/10. Statistical-equilibrium states of transition entropy Ω_T, agricultural marginal utility per automaton U_{Ma} and land use were then approximated by 500 iterations for each sample-point, both with $(\omega = 0.25)$ and without $(\omega = 0)$ anticipation (Fig. 6). Note that if we set parameter $\delta = 0$, the model reduces to its previous form (*4.4.1.3. Utility feedbacks and regrowth of nature*). Furthermore, that both agricultural land-use-state utilities and transition costs (Table 1) are no longer constant.

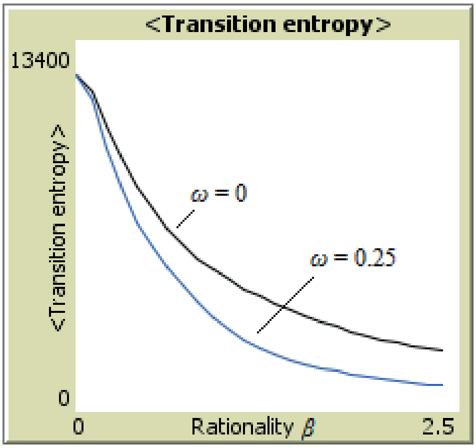

Fig. 6a. Statistical-equilibrium states—approximated by 500 iterations—of transition entropy Ω_T plotted against rationality β without and with anticipation, i.e., for $\omega = 0$ (black) and $\omega = 0.25$ (blue), respectively.

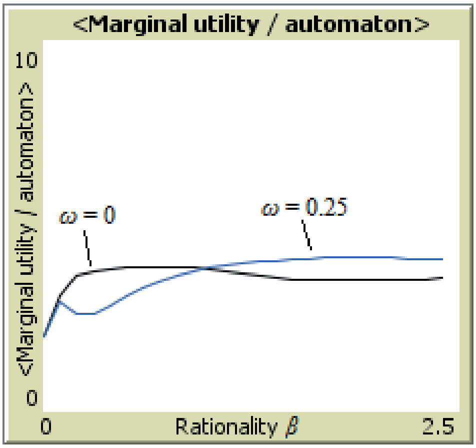

Fig. 6b. Statistical-equilibrium states—approximated by 500 iterations—of agricultural marginal utility U_{Ma} plotted against rationality β without and with anticipation, i.e., for $\omega = 0$ (black) and $\omega = 0.25$ (blue), respectively.

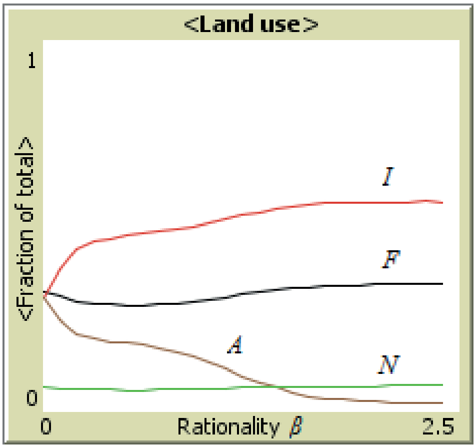

Fig. 6c. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I, A, N* and *F* plotted against rationality β without anticipation, i.e., for $\omega = 0$

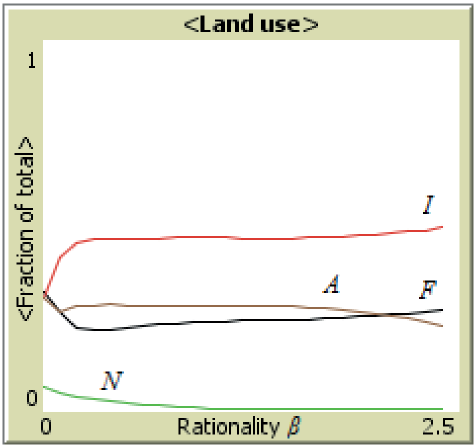

Fig. 6d. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I, A, N* and *F* plotted against rationality β with anticipation, i.e., for $\omega = 0.25$

Note: Length of Markov chain $n = 10$, feedback parameter $\varepsilon = 0.1$ and co-operation parameter $\delta = 0.5$. Red is high-input fraction *I* of total land use, brown is low-input fraction *A* of total land use, green is natural fraction *N* of total land use, black is fallow fraction *F* of total land use. Total land use is $I + A + N + F = 1, \forall t$.

Table 4. Statistical-equilibrium states—approximated by 500 iterations—of entropies Ω_T, marginal utilities U_{Ma} and land-use fractions *I*, *A*, *N* and *F* for $\beta \neq 0$.

(β,ω)	$<\Omega_T>$	$<U_{Ma}>$	$<I>$	$<A>$	$<N>$	$<F>$
$(1,0)$	4761.7	4.6	0.51	0.13	0.06	0.3
$(2.5,0)$	2029.1	4.4	0.58	0	0.07	0.35
$(1,0.25)$	2870.2	4.4	0.47	0.28	0.01	0.24
$(2.5,0.25)$	838.2	4.6	0.51	0.21	0	0.28

Note: Length of Markov chain $n = 10$, feedback parameter $\varepsilon = 0.1$ and co-operation parameter $\delta = 0.5$. *I* is high-input fraction of total land use, *A* is low-input fraction of total land use, *N* is natural fraction of total land use and *F* is fallow fraction of total land use. Total land use is $I + A + N + F = 1, \forall t$.

Entropic and economic behavior is similar to that of the previous model form without co-operation mechanism (*4.4.1.3. Utility feedbacks and regrowth of nature*), except that the model with anticipation performs better for sufficiently high β (Fig. 2b, Fig. 4b). That is, when the co-operation mechanism is included. For the model with anticipation, we see that high- and low-input agriculture are more stable compared to the model without co-operation mechanism, i.e., they are stable until around $\beta = 2$ (Fig. 6d) instead of until around $\beta = 1.25$ (Fig. 4d). Just as for the previous model form, we observe spectrums of statistical-equilibrium states for which marginal utility is stable for $\beta > 0.3$ (Fig. 6c) and $\beta = 1.25$ (Fig. 6d), without and with anticipation, respectively.

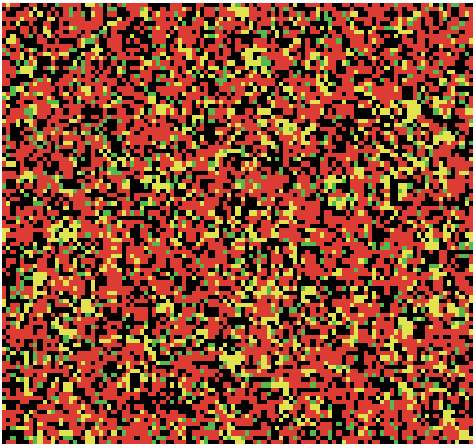

Fig. 7a. Landscape after 500 iterations for rationality $\beta = 1$ with anticipation $\omega = 0$

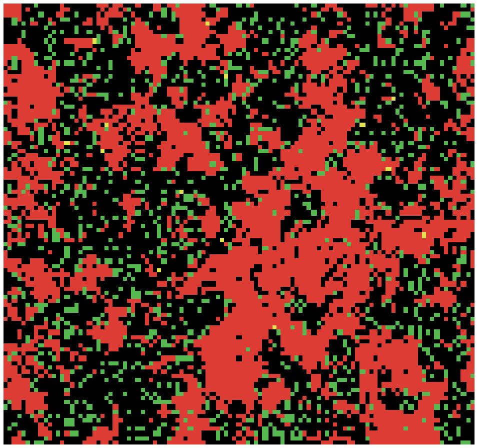

Fig. 7b. Landscape after 500 iterations for rationality $\beta = 2.5$ with anticipation $\omega = 0$

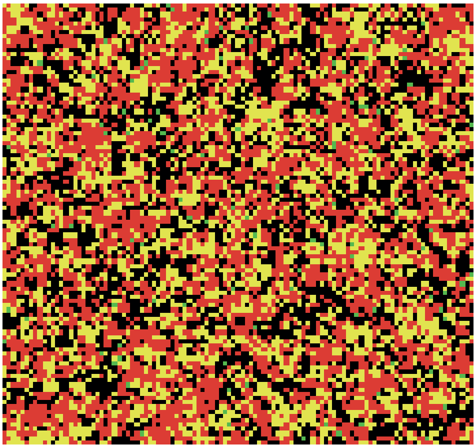

Fig. 7c. Landscape after 500 iterations for rationality $\beta = 1$ with anticipation $\omega = 0.25$

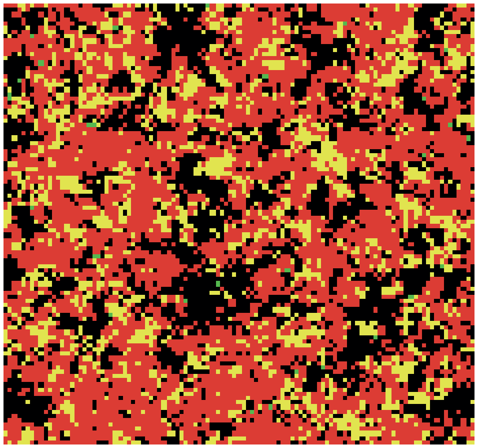

Fig. 7d. Landscape after 500 iterations for rationality $\beta = 2.5$ with anticipation $\omega = 0.25$

Note: Red is high-input fraction *I* of total land use, yellow is low-input fraction *A* of total land use, green is natural fraction *N* of total land use, black is fallow fraction *F* of total land use. Total land use is $I + A + N + F = 1, \forall t$.

Because the added co-operation mechanism is a spatial mechanism (*4.4. Temporal and spatial mechanisms*) automata no longer behave spatially independent. Periodically changing patterns of low- and high-input agriculture emerge (Fig. 7), although resulting landscapes are still somewhat similar to those without co-operation mechanism (Fig. 5). Upon increasing rationality from $\beta = 1$ (Fig. 7a, Fig. 7c) to $\beta = 2.5$ (Fig. 7b, Fig. 7d), spatial clustering increases and high-input agriculture increases while low-input agriculture strongly decreases (Table 4), both with (Figs. 7c–7d) and without (Figs. 7a–7b) anticipation. Finally, upon enabling automata to anticipate (Figs. 7c–7d), natural- and high-input land use decrease and low-input agriculture strongly increases (Table 4), compared to without anticipation (Figs. 7a–7b). This is true for both $\beta = 1$ (Fig. 7a, Fig. 7c) and $\beta = 2.5$ (Fig. 7b, Fig. 7d).

4.5. Discussion

The here-presented model has shown how simple individual-based land-use systems may generate complex behavior at aggregate level, which is a common feature of real-world land-use systems. It suggests that land-use systems can exhibit system complexity that can be disentangled into systematic processes. That is, aggregate complexity that is not solely attributable to effects of disorganization, and can be shown to be derived from systematic input complexity (*4.2. Introduction*). If we are too much inclined towards aggregate real-world drivers, empirical data, and statistics, it is more likely that we cannot disentangle input complexity. This obstacle prevents successful dynamic modeling of real-world complexity (Claessens et al., 2009). Conversely, if we are too much inclined towards abstraction, we are likely to lose the ability to validate results. Our model minimizes disorganized input complexity by its individual-based design, while retaining the possibility of validation. Input complexity is then most easily disentangled into reproducible systematic processes. Moreover, non-systematic temporal effects of input complexity will be filtered out by using statistical-equilibrium states. Therefore, we may expect it to perform better than either of these extremes. In the following subsections we discuss emergence and self-organization, how the different mechanisms give rise to observed complexity, and added value of the model.

4.5.1. *Emergence and self-organization*

Particular statistical-equilibrium states are emergent, because they are a result of individual behavior of many automata that could not have been predicted a priori (Strogatz, 2001; Liu et al., 2007). Therefore, also observed spectrums of statistical-equilibrium states (Fig. 2, Fig. 4, Fig. 6) are emergent, because they are a result of individual behavior of many automata that could not have been predicted a priori. However, there can be no self-organization between particular statistical-equilibrium states. That is, each particular state is obtained by one model run while there is no information exchange between model runs. Furthermore, until the addition of the co-operation mechanism automata do not interact (Fig. 2, Fig. 4). After adding the spatial co-operation mechanism to the temporal mechanisms already in effect, the model allows for spatio-temporal self-organization (Bao Le et al., 2011). Moreover, it can then exhibit complex systems behavior through non-linear interaction between automata.

4.5.2. *Temporal mechanisms*

Although both the choice model of utility maximization (*4.4.1.1. Utility maximization*) and Markov chains (*4.4.1.2. Anticipation*) have been well-known tools in the scientific land-use modeling community for decades, dynamic—real time—feedbacks between transition probabilities and choice model are scarce (Satake and Iwasa, 2006; Bao Le et al., 2008). We were inspired by the work of Satake and Iwasa (2006) which was improved and expanded by us, constructing a new model in the process. They only included perceptions of utility into their model (Satake and Iwasa, 2006, p. 372, eq. 2) and not perceptions of costs as well, as we have done in equation (3). The inclusion of perceptions of costs and benefits leads to the more general transition matrix $\mathbf{M}(n)$ given by equation (8), compared to $\mathbf{P}(n)$ given by equation (2) which is a special case of $\mathbf{M}(n)$ for zero transition costs. Furthermore, we differentiate between high- and low-input land use whereas they only define agricultural land use (Satake and Iwasa, 2006, p. 373). Regrowth of nature is treated as part of decision making by Satake and Iwasa (2006, p. 376, eq. 17), while we have treated it as an independent gradual process (*4.4.1.3. Utility feedbacks and regrowth of nature*). Moreover, they did not add any other temporal or spatial mechanisms (*4.4. Temporal and spatial mechanisms*).

Therefore, we have not only improved the work of Satake and Iwasa (2006) and constructed a new model in the process, but we have also added another temporal mechanism allowing for more advanced decision making. That is, utility-feedback mechanisms make it possible for land-use-state utilities to decrease as a consequence of utility-maximizing decisions that cause automata to either convert into or remain in high- or low-input states (*4.4.1.3. Utility feedbacks and regrowth of nature*). This causes entropies and agricultural marginal utilities (Fig. 4, Table 3) to be much higher and lower, respectively, compared to without feedback mechanisms (Fig. 2, Table 2). This could be interpreted as a result of facing more realistic conditions in general. Finally, our work follows the conceptual approaches of pattern-oriented modeling (Grimm et al., 2005, 2006) and statistical-equilibrium states (*4.3.5. Model output*), while the work of Satake and Iwasa (2006) does not allow for landscape visualization or pattern formation and follows an opposite approach of investigating real-time behavior only, respectively. Note that combining the temporal mechanisms of utility maximization and utility feedbacks can already generate different emergent land use- and land-use patterns, for varying levels of individual rationality- and foresight (Figs. 4–5).

4.5.3. *Spatial mechanisms*

The co-operation mechanism is an abstraction of how agricultural co-operatives can lead to more efficient sharing of costs. It allows automata to indirectly affect their nearest neighbor's transition probabilities into high- and low-input agricultural states, by lowering transition costs proportionally to the number of neighboring automata in such states (Jepsen et al., 2006; Moreno et al., 2009; Wickramasuriya et al., 2009). Because lowering transition costs exponentially affects the outcome of equation (3) and thereby of the utility-maximization mechanism, automata become spatially interdependent in a non-linear way. This causes complex systems behavior, in tandem with temporal mechanisms already in effect. Complex systems behavior generates different dynamical emergent land-use patterns, for varying levels of individual rationality- and foresight (Fig. 7). Furthermore, it causes changes in emergent land use- and agricultural marginal utility, compared to without complex systems behavior, for varying levels of individual rationality- and foresight (Fig. 4, Fig. 6).

4.5.4. *Intensification*

In some cases, resulting emergent behavior can be interpreted as intensification of agriculture. This is explained in detail in the next paragraph. Overall, when considerations of the future do not matter $(\omega = 0)$, we cannot say with certainty that intensification emerges. When considerations of the future do matter $(\omega = 0.25)$, we can say with certainty that intensification emerges for $\beta > 0.3$.

For utility-maximization- and utility-feedback mechanisms with anticipation (Fig. 8a), we see that total agricultural land use remains nearly constant at increasing agricultural marginal utility for $0.3 < \beta < 1.25$ (Fig. 4b, Fig. 8a). That is, changes in total agricultural land use are negligible, compared to changes in agricultural marginal utility. Because automata are units of area, we can interpret agricultural marginal utilities (Fig. 2b, Fig. 4b, Fig. 6b) as abstractions of average yields per unit area. Therefore, this behavior could be interpreted as intensification due to yield increase. However, for $1.25 \leq \beta \leq 2.5$, agricultural marginal utility remains nearly constant (Fig. 4b). Total agricultural land use strongly decreases, while intensive land use increases (Fig. 8a). That is, now changes in agricultural marginal utility are negligible, compared to changes in total agricultural land use. This could be interpreted as intensification of agriculture due to substitution of land for inputs (Mandemaker et al., 2011). Complex systems behavior generated by adding the co-operation mechanism, causes intensification due to yield increase to emerge for $0.3 < \beta < 2$ (Fig. 6b, Fig. 8b), instead of for $0.3 < \beta < 1.25$ (Fig. 4b, Fig. 8a). That is, intensification due to yield increase at constant total agricultural land use emerges over a larger range of rationality.

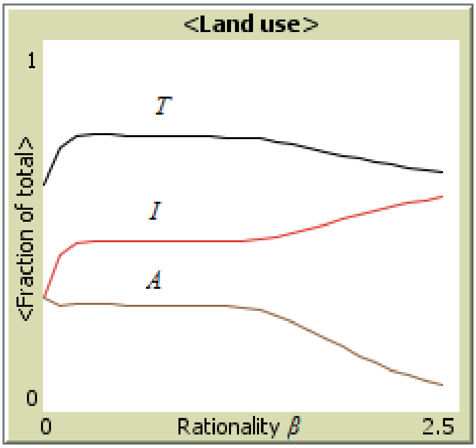

Fig. 8a. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I*, *A* and *T* plotted against rationality β with anticipation, i.e., $\omega = 0.25$, for utility-maximization- and utility-feedback mechanisms.

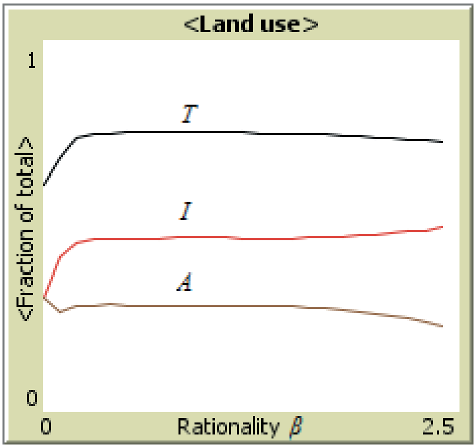

Fig. 8b. Statistical-equilibrium states—approximated by 500 iterations—of land-use fractions *I*, *A* and *T* plotted against rationality β with anticipation, i.e., $\omega = 0.25$, for utility-maximization-, utility-feedback- and co-operation mechanisms.

Note: Length of Markov chain $n = 10$, feedback parameter $\varepsilon = 0.1$ (Fig. 8a, Fig. 8b). Co-operation parameter $\delta = 0.5$ (Fig. 8b). Red is intensive fraction *I* of total land use, brown is extensive fraction *A* of total land use and black is total agricultural fraction *T* of total land use $(T = I + A)$. Total land use is $I + A + N + F = 1, \forall t$.

4.5.5. *Validation and value added*

Pattern-Oriented Modeling (POM) (Grimm et al., 2005, 2006; Piou et al., 2009) attempts to reproduce real-world aggregate patterns with emergent—complex systems—behavior. It is believed that POM holds the potential to further increase understanding of land-use systems that are too complex to be understood by empirical analysis alone (Grimm et al., 2005; Evans and Manson, 2007; Liu et al., 2007; Wiegand et al., 2008). The concept of statistical-equilibrium state enables us to better approximate real-world systematic properties by filtering out non-systematic temporal variations. Furthermore, statistical-equilibrium states are reproducible emergent properties of systematic complexity, and not of—disorganized—input complexity. In effect, we are treating the landscape as analogous to a thermo-dynamical system that can traverse a spectrum of equilibrium states.

To quantify and compare generated land-use patterns to real-world land-use patterns, we could apply patch-level pattern metrics from landscape ecology, e.g., patch distribution- and density and/or patch-shape complexity (McGarigal, 2006). Furthermore, we could investigate—partial—autocorrelation of patches (Overmars et al., 2003). This would allow us to investigate the relation between pattern indices and systematic processes (Li and Wu, 2004). If the land-use pattern generated by a specific combination of mechanisms—and parameters—matches a real-world land-use pattern, there is quantitative evidence for those mechanisms key to that real-world landscape. Therefore, systematically generated patterns can be used in an attempt to filter out underlying processes.

However, as soon as real-world aggregate land-use patterns do come into play, so does disorganized complexity (*4.2. Introduction*). That is, if real-world- and generated patterns match, this could also be caused by processes or combinations of processes we did—or could—not include. Furthermore, our model could also be subject to disorganized input complexity introduced by real-world maps. Clearly, for any situation involving real-world complexity of landscapes, it is impossible to exclude input complexity entirely.

4.6. Conclusions

Combining the simple yet plausible temporal mechanisms of utility maximization, utility feedbacks, and anticipation can generate different emergent land-use patterns. Furthermore, it can generate two different types of emergent intensification of agriculture. That is, intensification due to yield increase at constant total agricultural land use, or due to substitution of agricultural land for inputs. Complex systems behavior caused by addition of the simple and plausible spatial mechanism of co-operation, can generate different dynamical emergent land-use patterns. Furthermore, it causes intensification due to yield increase to emerge over a larger range of rationality. Both with and without complex systems behavior, intensification only emerges when automata are allowed to anticipate. Our pattern-oriented land-use-transition model allows for meaningful approximation of real-world agricultural land-use systems by emergent—complex systems—behavior. Through an iterative process of comparing land-use patterns generated by different combinations of mechanisms with—and tuning parameters of those mechanisms to—real-world land-use patterns. Different patterns generated by different combinations of mechanisms—and parameters—can be used in an to attempt to filter out underlying processes. Our model minimizes disorganized input complexity while retaining the possibility of validation. Statistical-equilibrium states are reproducible emergent properties of systematic complexity, and not of—disorganized—input complexity. When applied, non-systematic temporal effects of input complexity will be filtered out by using statistical-equilibrium states.

Feathers touched down softly,
Upon my mind's face,
You were the backbone of kindness,
My cornerstone of grace.

5

Pattern-oriented individual-based modeling of spatially explicit agricultural landscapes: A scenario analysis of effects of state-centric governance and top-down policy instruments on protection of nature

Submitted to Agricultural Systems: Mandemaker, M., Bakker, M., and Veldkamp, A.

Abstract

To investigate under which conditions nature could be protected from agriculture in an optimal way, individual farmers were subjected to different state-centric governance settings in a spatially explicit pattern-oriented individual-based land-use model (CORA). One state-centric governance setting was assumed to be determined by the quality of the investment climate, reflected by the quality of the state-centric governance dimension “Regulatory quality”. The other was assumed to be determined by the level of entrepreneurial awareness, reflected by the quality of the state-centric governance dimension “Government effectiveness”. Together, these could be combined into four state-centric governance settings: “Low Entrepreneurial Awareness and Low Quality of Investment Climate” (I); “Low Entrepreneurial Awareness and High Quality of Investment Climate” (II); “High Entrepreneurial Awareness and Low Quality of Investment Climate” (III); and “High Entrepreneurial Awareness and High Quality of Investment Climate” (IV). Farmers were subjected to two different top-down policy instruments in each state-centric governance setting: subsidies and fines. For all state-centric governance settings, a fine was likely to be the most cost-effective policy instrument for protection of nature, rather than a subsidy. The most effective- and second-most effective protection of nature were generated by applying fines, under state-centric governance setting III and IV, respectively.

Keywords: co-operation; governance; agriculture; land-use pattern; utility; complexity; scenario.

5.1. Introduction

It is believed that Pattern-Oriented Modeling (POM) holds the potential to further increase understanding of land-use systems that are too complex to be understood by empirical analysis alone (Grimm et al., 2005; Evans and Manson 2007; Liu et al., 2007; Wiegand et al., 2008). POM attempts to reproduce real-world aggregate patterns with emergent behavior (Grimm et al., 2005, 2006; Piou et al., 2009). Recently, more and more successful attempts have been made to view land-use systems as dynamic social-ecological systems, from the perspective of individual-based modeling (Parker et al., 2003; Jepsen et al., 2006; Brown et al., 2008; Lopez-Carr et al., 2011; Mandemaker et al., 2014). By combining pattern-oriented and individual-based modeling techniques, it should be possible to incorporate dynamic complexity of interactions between farmers and nature in a verifiable way. Furthermore, by incorporating economic behavior in a way that does not oversimplify it to keep complexity at a manageable level, an attempt could be made to help bridge the gap between landscape ecology and economics (Veldkamp et al., 2011). Conventionally, the field of Walrasian economics focuses on the behavior of agents, without explicit spatial dimensions or interactions (van der Veen and Otter, 2001, 2003). Core assumptions of simplification are that rational decision making occurs through optimization, that preferences are stable in time, and that forward looking individual farmers can instantaneously update their knowledge of the entire system, at any time (Vatn, 2005).

A pattern-oriented individual-based land-use transition model that allows for utility maximization at varying levels of complexity and rationality (CORA) was made for agricultural landscapes (Mandemaker et al., 2014). This model was designed to tackle dynamic complexity as well as to incorporate more realistic Walrasian economic behavior, in a spatially explicit way. Its aggregate land-use patterns are the product of local spatially explicit optimization problems that may be resolved through the economic behavior of individual farmers simultaneously facing local environmental and state-centric governance constraints. Preferences are spatially explicit and no longer required to be stable in time, individual farmers can interact spatially and anticipate future consequences of decisions, and individual farmers are rationally bounded. Moreover, individual farmers are subjected to imperfect information. That is, they only have access to limited spatial and temporal information to base their land-use decisions on. The CORA model was applied to a fictive landscape in which land-use preferences- and transition costs varied across space. To investigate under which conditions nature could be protected from agriculture in an optimal way, farmers were subjected to four different state-centric governance settings: “Low Entrepreneurial Awareness and Low Quality of Investment Climate”; “Low Entrepreneurial Awareness and High Quality of Investment Climate”; “High Entrepreneurial Awareness and Low Quality of Investment Climate”; and “High Entrepreneurial Awareness and High Quality of Investment Climate”. Furthermore, individual farmers were subjected to two different top-down policy instruments for each state-centric governance setting: subsidies and fines. This led to eight top-down policy scenarios for protection of nature; one subsidy scenario and one fine scenario for each state-centric governance setting.

5.2. Methods

5.2.1. *CORA model*

5.2.1.1. *Land-use states*

Land can be in a natural state, in a high- or low-input agricultural state, or in a fallow state. High-input agricultural land is used more intensively than low-input land. Low-input agriculture causes soil-nutrient depletion, while high-input agriculture results in increased sensitivity to diseases due to e.g., mono cultivation and sterilization of the soil. Conversely, high-input agriculture does not cause soil-nutrient depletion, while low-input agriculture does not cause increased sensitivity to diseases. Therefore, negative effects of low- and high-input land use may be assumed to be independent.

5.2.1.2. *Land-use-state transitions*

Individual farmers are allowed to convert land to the fallow state by clearing of natural land or by abandonment of high- or low-input agricultural states. Individual farmers are allowed to convert land to agriculture by taking fallow or natural land into production, associated with investment costs. Finally, decision makers can convert from high-input- to low-input agriculture and vice versa, associated with opportunity costs. That is, these costs are determined by what is lost by not remaining in a particular agricultural state. Regrowth of nature after clearing or abandonment is a gradual and natural process and not the result of a single iteration of decision making. Therefore, land can only be in a state of natural land because it remained in that state, or land remained in the fallow state sufficiently long for nature to regrow (fallowing). Whenever land remained in a state of natural land for more than one model iteration, nature was assumed to be protected from agriculture.

5.2.1.3. *Structure*

Within the CORA model (Fig. 1), cellular automaton cells (10,000) represent abstractions of individual farmers operating on single patches of land in a fixed two-dimensional grid. Based on utilities and transition costs, a stochastic utility-maximization mechanism determines individual choices. How stochastic this mechanism operates is determined by individual rationality, regulated in between extremes of – purely stochastic – irrational decision making and – purely deterministic – rational decision making. An anticipation mechanism allows automata to project and compare utility gained from the possible different decision chains, departing from their present land-use state up to an arbitrary number of steps into the future. They then base present decisions on these future projections. Furthermore, effects of high- and low-input agriculture are modeled by independent utility-feedback mechanisms that operate on automata in high- and low-input states, respectively. More efficient sharing of costs by larger groups of automata is modeled by a co-operation mechanism. This mechanism causes transition costs into agricultural states to decrease, proportional to the count of neighboring agricultural states.

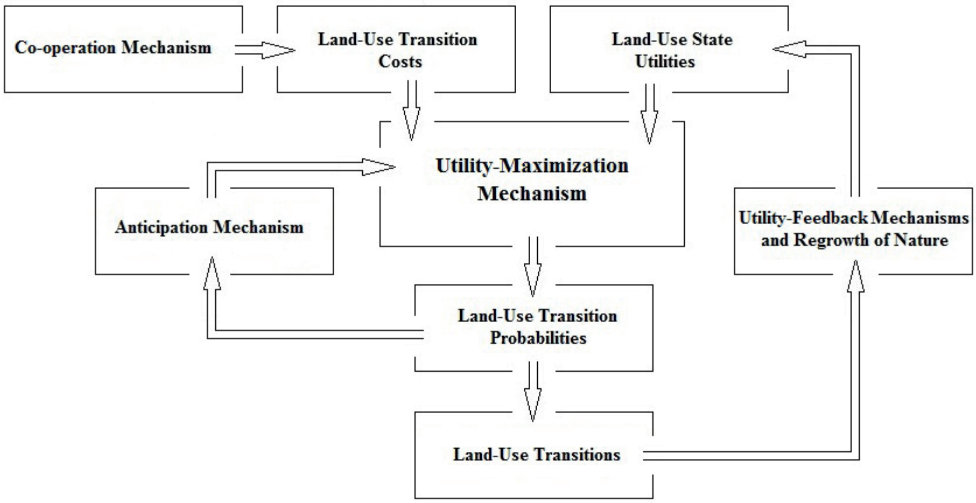

Fig. 1. Flowchart of the CORA model. Source: Mandemaker et al., 2014.

Note. A full explanation of these mechanisms and specific settings of their parameters may be found in Chapter 4 (*4.4. Temporal and spatial mechanisms*).

5.2.1.4. *Model output*

The CORA model generated six system-state variables, of which five were land uses and one was utility derived from these land uses. The five land uses were low-input agriculture, high-input agriculture, protected nature, nature by regrowth, and fallow land. Furthermore, the model generated the land-use patterns associated with these system-state variables. After 500 iterations (the total runtime of one modelrun), generated landscapes could be assumed to be in a state of statistical equilibrium. This is because within the CORA model, temporal averages of system-state variables no longer noticeably change upon further increasing the number of iterations per modelrun (Mandemaker et al., 2014). Hence, time did not play a role in the analysis of generated system-state variables and land-use patterns. Because this study investigated how well nature could be protected from agriculture in different scenarios, all landscapes were assumed to be unaffected by land use, initially. That is, initial land cover was set to 100 % nature for all modelruns.

5.2.2. ***Spatial distribution of utilities and costs***

All land-use states were assigned land-use-state utilities, and all transitions were assigned a transition cost (Table 1). To construct a fictive but realistic landscape, five ASCII-files were imported into the CORA model. Four of these files contained the values and spatial distributions of the four land-use-state utilities, over all individual patches. Distributions of land-use-state utilities were constructed in ArcGIS 10.1, in such a way that the average value calculated from their respective ASCII-files, was equal to their respective values in Table 1. Values deviated no more than one Standard Deviation from this average (plus or minus two). To preserve conceptual consistency of the land-use transition framework defined for the CORA model by Mandemaker et al. (2014), the original differences between land-use-state utilities (Table 1) needed to be preserved for all individual patches. This is because this land-use transition framework was defined conceptually through these differences (Table 1). To do so, it was necessary to use identical spatial distributions for all land-use-state utilities, centered around their respective averages (Table 1). This also provided a means of comparing results for a specific state-centric governance setting, with and without a top-down policy instrument superposed on this constraint (a baseline). That is, only if such a policy instrument preserved conceptual consistency as well. Furthermore, behavior under different state-centric governance settings could be compared in this way (all other things being equal). The fifth ASCII-file contained the values and spatial distribution of the transition cost associated with making the transition from nature to fallow land (Table 1), over all individual patches. To better compare the results of simulated top-down policy instruments later, this particular transition cost was spatially varied in the same way as the initial land-use-state utility of natural land. Transition costs associated with the transitions from nature to low- or high-input agriculture necessarily also followed from this fifth ASCII-file (Table 1).

Table 1. Relative perceptions of benefits – land-use-state utilities – (U) and transition costs (C).

I $(U_I = 10)$	*A* $(U_A = 8)$	*N* $(U_N = 2)$	*F* $(U_F = 4)$	
$(C_{II} = 0)$	$(C_{IA} = 10)$	-	$(C_{IF} = 0)$	*I*
$(C_{AI} = 8)$	$(C_{AA} = 0)$	-	$(C_{AF} = 0)$	*A*
$(C_{NI} = 9.6)$	$(C_{NA} = 7.1)$	$(C_{NN} = 0)$	$(C_{NF} = 2)$	*N*
$(C_{FI} = 7.6)$	$(C_{FA} = 5.1)$	-	$(C_{FF} = 0)$	*F*

Note. The first row contains land-use-state utilities. Transition costs should be read from row to column. Empty table entries correspond to non-occurring transitions. *I* is high-input land use, *A* is low-input land use, *N* is natural land use, and *F* is fallow land use. Source: Mandemaker et al., 2014.

5.2.3. *State-centric governance settings and top-down policy scenarios*

5.2.3.1. *State-centric governance settings*

In the CORA model, the parameter $\beta \in [0, \infty)$ regulates rationality of individual behavior (Mandemaker et al., 2014). For $\beta = 0$, utility maximization cannot occur because individual farmers then behave purely stochastic (irrational). For non-zero increasing values of β, individual farmers will behave more and more rational. The ability of individual farmers to process information on which they base land-use decisions is known to be related to general education and governmental educational programs designed to raise farmers' entrepreneurial awareness (refs). Therefore, it is assumed that the higher farmers' entrepreneurial awareness, the more rational their land-use decisions will be. That is, the rationality parameter β is assumed to model farmers' entrepreneurial awareness. Furthermore, the anticipation mechanism (Fig. 1) that allows individual farmers to project and compare the utility that would be gained from different decisions, and then base present decisions on these future projections, is regulated by parameter $\omega \in [0,1]$. For $\omega = 0$, expectations from future decisions will be negligible and will not affect decision making. For non-zero increasing values of ω, expectations from future decisions will affect decision making more and more. This allows individual farmers to invest in their future, if they are able to identify and exploit

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opportunities. The higher the quality of the investment climate the more and further farmers are assumed to anticipate on these projections, modeled by a higher value of the anticipation parameter. Therefore, anticipation parameter ω was assumed to correspond with the quality of the investment climate, i.e.,, how much investment potential there is available for individual farmers. Following the parameter settings of Mandemaker et al. (2014), $\omega = 0$ was assumed to correspond with ‘Low Quality of Investment Climate’, and $\omega = 0.25$ was assumed to correspond with ‘High Quality of Investment Climate’. Furthermore, $\beta = 1$ was assumed to correspond with ‘Low Entrepreneurial Awareness’, and $\beta = 2.5$ was assumed to correspond with ‘High Entrepreneurial Awareness’.

The general level and quality of education and the ability to actually take rationally preferred decisions depend on the quality of the state-centric governance dimension “Government effectiveness”, responsible for the delivery of such public services (Kaufmann, 2009, 2010). Therefore, the rationality parameter reflects the quality of this dimension of governance. Similarly, the quality of the investment climate depends on the quality of the state-centric governance dimension “Regulatory quality”, responsible for the promotion of private-sector development (Kaufmann, 2009, 2010). Therefore, the anticipation parameter reflects the quality of this dimension of governance. This leads to four different state-centric governance settings, to which farmers will need to adapt (Fig. 2).

5.2.3.2. *Top-down policy scenarios*

In each of the four state-centric governance settings, individual farmers were subjected to two different top-down policy instruments: subsidies and fines. This led to eight top-down policy scenarios for protection of nature; one subsidy scenario and one fine scenario for each state-centric governance setting. Both subsidies and fines were modeled in a way that did not corrupt the conceptual consistency of the land-use transition framework of the CORA model (5.2.2. *Spatial distribution of utilities and costs*). Subsidies were modeled by increments in land-use-state utility of natural land (Table 1), causing individual farmers to perceive nature as more valuable than agriculture, possibly resulting in the protection of nature. For each state-centric governance setting, 50 consecutive model runs occurred to simulate the effects of subsidies, incrementing the perceived value of nature by 0.1 each run (identically for all individual patches).

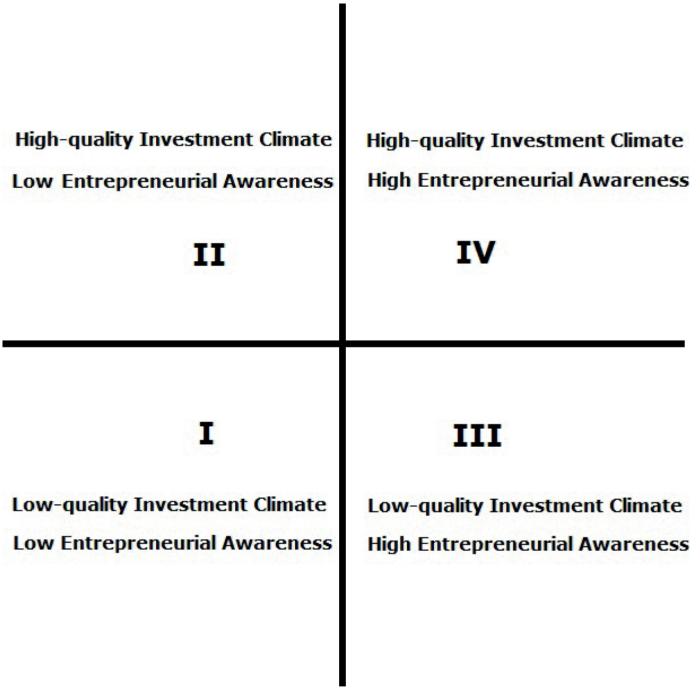

Fig. 2. The four state-centric governance settings.

Similarly, fines were modeled by increments in the cost (Table 1) associated with the transition from natural land to fallow land, discouraging individual farmers to clear natural land by causing them to perceive it as more costly, thereby encouraging the protection of nature. To compare the effects of fines with those of subsidies, this transition cost was incremented in a way that was identical to how the perceived value of nature was incremented for the subsidy scenarios. That is, for each state-centric governance setting, 50 consecutive model runs occurred to simulate the effects of fines, incrementing the cost of clearing by 0.1 each run (identically for all individual patches). Incrementing this transition cost also caused the costs associated with the transitions from nature to low- and high-input agriculture to be incremented in an identical way (Table 1).

5.3. Results

5.3.1. *System-state variables*

5.3.1.1. *Land use*

Figs. 3–4 show the subsidy- and fine-scenario results for land use, belonging to state-centric governance settings I and II (Fig. 3), and III and IV (Fig. 4), respectively. Each scenario was constructed from 50 samples in total, with a sample size of 0.1. For each of these samples, land uses were averaged over the total runtime of one modelrun (500 iterations), after which generated landscapes could be assumed to be in a state of statistical equilibrium (Mandemaker et al., 2014).

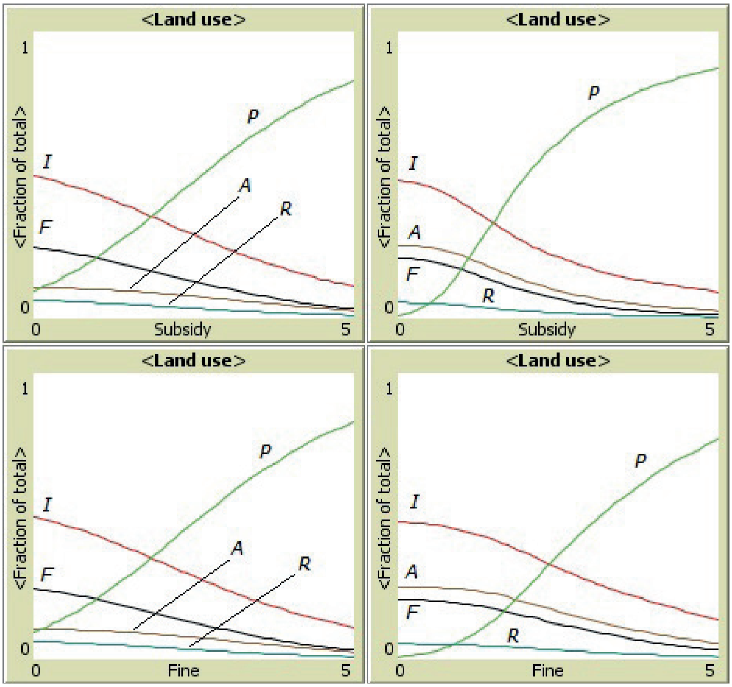

Fig. 3. Subsidy scenario I (upper left), fine scenario I (lower left), subsidy scenario II (upper right), fine scenario II (lower right). A is low-input agriculture, I is high-input agriculture, P is protected nature, R is nature from regrowth, and F is fallow land.

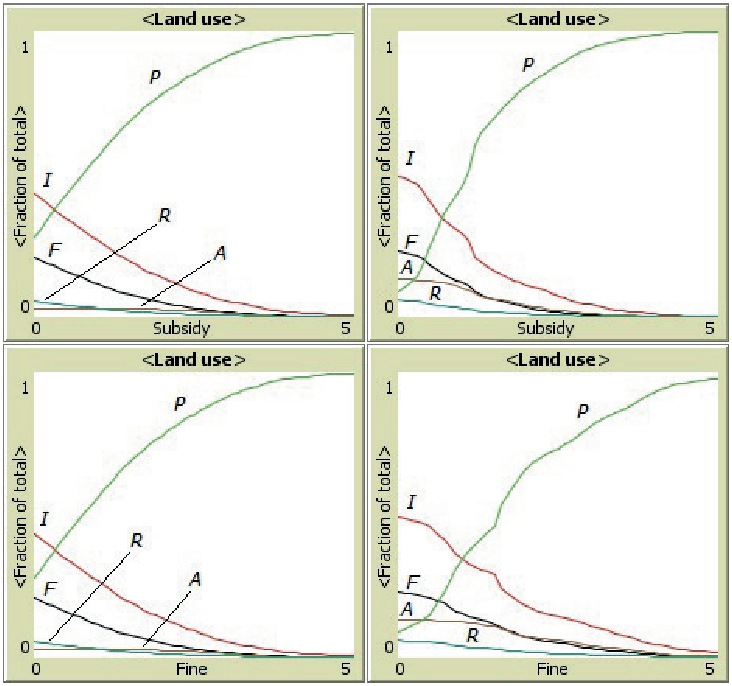

Fig. 4. Subsidy scenario III (upper left), fine scenario III (lower left), subsidy scenario IV (upper right), fine scenario IV (lower right). A is low-input agriculture, I is high-input agriculture, P is protected nature, R is nature from regrowth, and F is fallow land.

5.3.1.2. *Utility*

Figs. 5–6 show the subsidy- and fine-scenario results for marginal utility per automaton cell, belonging to state-centric governance settings I and II (Fig. 5), and III and IV (Fig. 6), respectively. Each scenario was constructed from 50 samples in total, with a sample size of 0.1. For each of these samples, marginal utility per automaton cell was computed by dividing the sumtotal of utility (yielded by all automaton cells together) by the total number of automaton cells (every iteration). This was then averaged over the total runtime of one modelrun (500 iterations), after which generated landscapes could be assumed to be in a state of statistical equilibrium (Mandemaker et al., 2014).

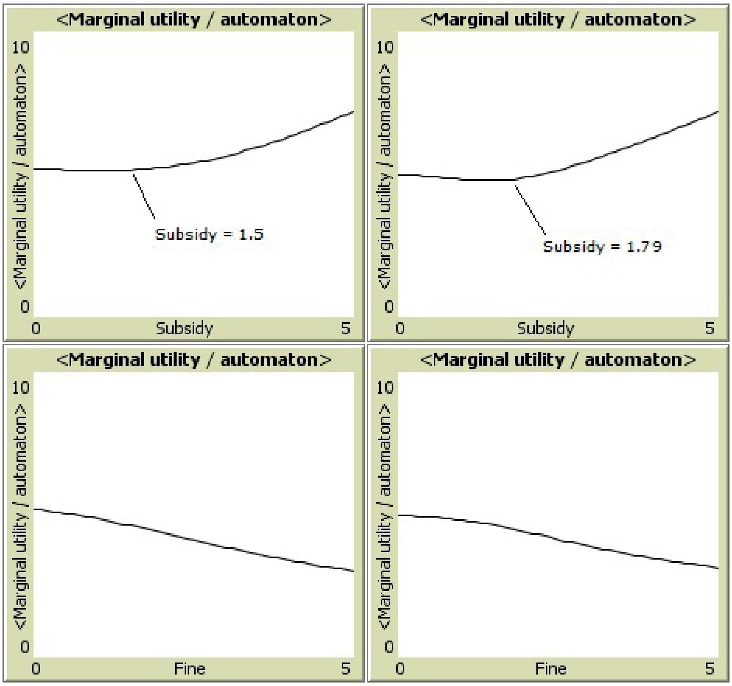

Fig. 5. Subsidy scenario I (upper left), fine scenario I (lower left), subsidy scenario II (upper right), fine scenario II (lower right). For values of subsidy greater than 1.5, utilities of subsidy- and fine scenario I diverged much faster (left). For values of subsidy greater than 1.79, utilities of subsidy- and fine scenario II diverged much faster (right).

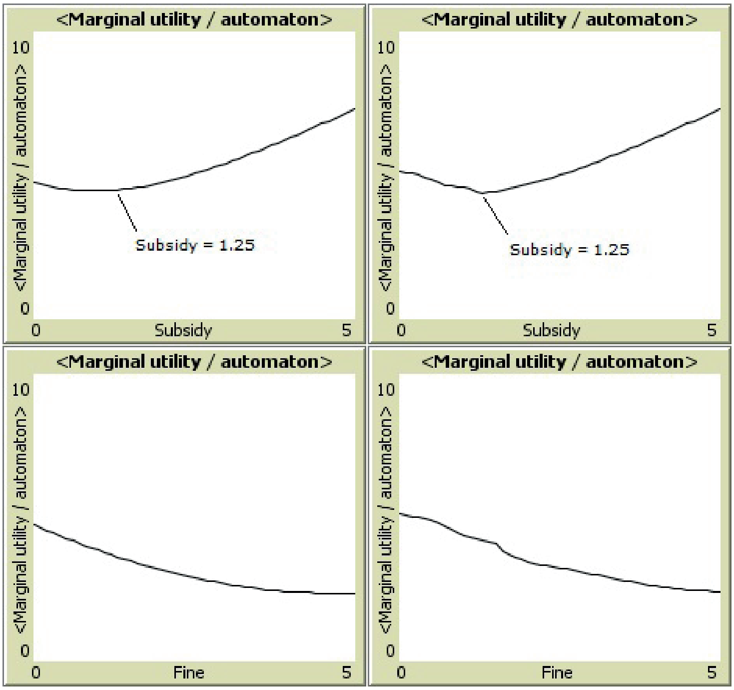

Fig. 6. Subsidy scenario III (upper left), fine scenario III (lower left), subsidy scenario IV (upper right), fine scenario IV (lower right). For values of subsidy greater than 1.25, utilities of subsidy- and fine scenario III diverged much faster (left). For values of subsidy greater than 1.25, utilities of subsidy- and fine scenario IV diverged much faster (right).

5.3.2. *Land-use patterns*

Figs. 7–10 show the land-use patterns for the subsidy- and fine scenarios belonging to state-centric governance settings I, II, III, and IV (Fig. 2), respectively. Subsidies and fines ranged from a minimum of zero to a maximum of five. All land-use patterns resulted from one modelrun (500 iterations), after which generated landscapes could be assumed to be in a state of statistical equilibrium (Mandemaker et al., 2014). For state-centric governance setting I, “Low Entrepreneurial Awareness and Low Quality of Investment Climate”, individual farmers generated a baseline landscape that was dominated by high-input agriculture (Fig. 7 upper- and lower left). With moderately clustered low-input agriculture across the middle. Furthermore, severely and moderately fragmented protected nature was generated in the upper-left- and lower-right corner, respectively. Corresponding baseline values of system-state variables could be observed in the left-hand sides of Fig. 3 and Fig. 5 (at zero subsidy/fine). Upon introducing subsidies (Fig. 7 upper middle, Fig. 7 upper right) and fines (Fig. 7 lower middle, Fig. 7 lower right), an expansion of protected area of nature could be observed, starting from the lower-right corner. Furthermore, an increasing fragmentation of agriculture could be observed.

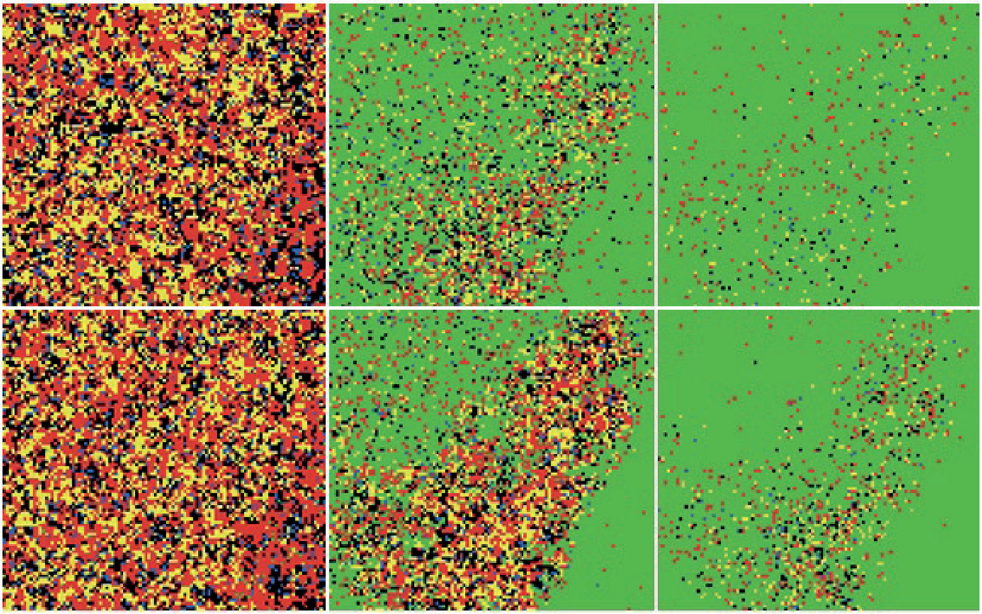

Fig. 7. Subsidy scenario I (upper), fine scenario I (lower). Zero (baseline) subsidy and fine (upper- and lower left, respectively); half of maximal (2.5) subsidy and fine (upper- and lower middle, respectively); and maximal (5) subsidy and fine (upper- and lower right, respectively). Yellow is low-input agriculture, red is high-input agriculture, green is protected nature, blue is nature from regrowth, and black is fallow land.

For state-centric governance setting II, "Low Entrepreneurial Awareness and High Quality of Investment Climate", individual farmers generated a baseline landscape that was severely dominated by low- and high-input agriculture (Fig. 8 upper- and lower left). With moderately clustered low-input agriculture across the landscape. Furthermore, the lower-right corner was dominated by high-input agriculture. Corresponding baseline values of system-state variables could be observed in the right-hand sides of Fig. 3 and Fig. 5 (at zero subsidy/fine). Upon introducing subsidies (Fig. 8 upper middle, Fig. 8 upper right) and fines (Fig. 8 lower middle, Fig. 8 lower right), an expansion of protected area of nature starting could be observed, particularly in the upper-left- and lower-right corners. Furthermore, an increasing fragmentation of agriculture could be observed, as well as differences in degrees of fragmentation.

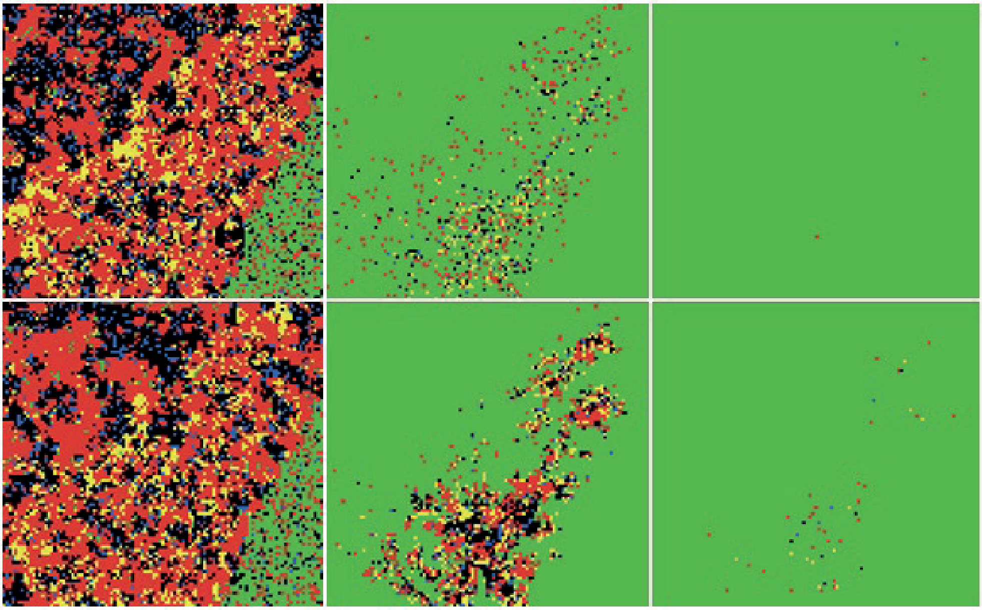

Fig. 8. Subsidy scenario II (upper), fine scenario II (lower). Zero (baseline) subsidy and fine (upper- and lower left, respectively); half of maximal (2.5) subsidy and fine (upper- and lower middle, respectively); and maximal (5) subsidy and fine (upper- and lower right, respectively). Yellow is low-input agriculture, red is high-input agriculture, green is protected nature, blue is nature from regrowth, and black is fallow land.

For state-centric governance setting III, "High Entrepreneurial Awareness and Low Quality of Investment Climate", individual farmers generated a baseline landscape that was least dominated by agriculture (Fig. 9 upper- and lower left). With moderately clustered high-input agriculture in the upper-left corner, and strongly clustered low- and high-input agriculture in the middle. Furthermore, moderately and strongly clustered protected nature was generated in the upper-left- and lower-right corner, respectively. Corresponding baseline values of system-state variables could be observed in the left-hand sides of Fig. 4 and Fig. 6 (at zero subsidy/fine). Upon introducing subsidies (Fig. 9 upper middle, Fig. 9 upper right) and fines (Fig. 9 lower middle, Fig. 9 lower right), an expansion of protected area of nature could be observed, starting from the upper-left- and lower-right corners. Furthermore, an increasing fragmentation of clusters of remaining (mainly high-input) agriculture could be observed.

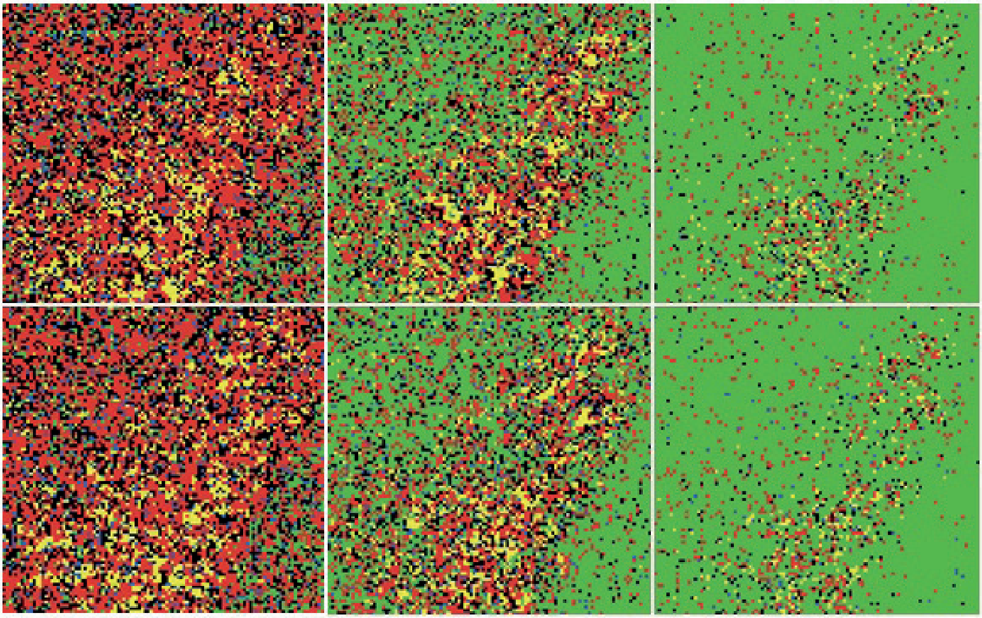

Fig. 9. Subsidy scenario III (upper), fine scenario III (lower). Zero (baseline) subsidy and fine (upper- and lower left, respectively); half of maximal (2.5) subsidy and fine (upper- and lower middle, respectively); and maximal (5) subsidy and fine (upper- and lower right, respectively). Yellow is low-input agriculture, red is high-input agriculture, green is protected nature, blue is nature from regrowth, and black is fallow land.

For state-centric governance setting IV, “High Entrepreneurial Awareness and High Quality of Investment Climate”, individual farmers generated a baseline landscape that was dominated by high-input agriculture (Fig. 10 upper- and lower left). With moderately clustered low-input agriculture in the middle, and strongly clustered high-input agriculture in the upper-left corner. Furthermore, strongly clustered protected nature was generated in the lower-right corner. Corresponding baseline values of system-state variables could be observed in the right-hand sides of Fig. 4 and Fig. 6 (at zero subsidy/fine). Upon introducing subsidies (Fig. 10 upper middle, Fig. 10 upper right) and fines (Fig. 10 lower middle, Fig. 10 lower right), an expansion of protected area of nature could be observed, starting from the lower-right corner. Furthermore, an increasing fragmentation of (clusters of) remaining agriculture could be observed, as well as differences in degrees of fragmentation.

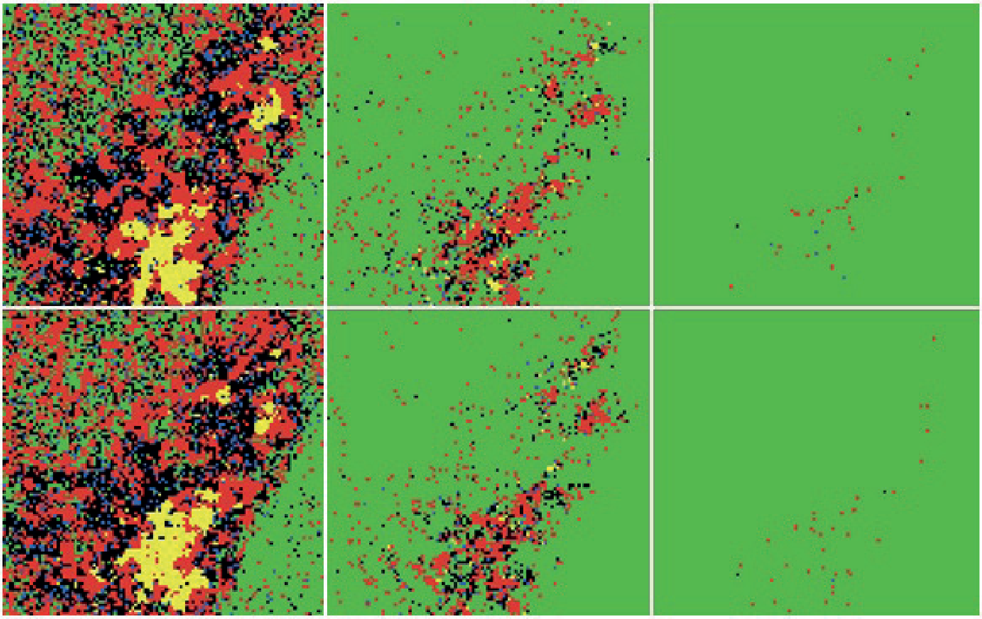

Fig. 10. Subsidy scenario IV (upper), fine scenario IV (lower). Zero (baseline) subsidy and fine (upper- and lower left, respectively); half of maximal (2.5) subsidy and fine (upper- and lower middle, respectively); and maximal (5) subsidy and fine (upper- and lower right, respectively). Yellow is low-input agriculture, red is high-input agriculture, green is protected nature, blue is nature from regrowth, and black is fallow land.

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5.4. Discussion

5.4.1. *Within state-centric governance settings*

In this subsection, differences between subsidy- and fine scenarios were discussed in an attempt to identify effects of cross-level and cross-scale interactions, and which policy instrument protects nature best, given a specific state-centric governance setting. That is, for each state-centric governance setting (Fig. 2), differences between the subsidy- and fine scenario belonging to that state-centric governance setting were discussed.

5.4.1.1. *Low Entrepreneurial Awareness and Low Quality of Investment Climate (I)*

For "Low Entrepreneurial Awareness and Low Quality of Investment Climate", state-centric governance setting I, comparing the subsidy scenario to the fine scenario showed that land uses were affected nearly identically in both scenarios (Fig. 3 left). Furthermore, that land-use patterns were affected nearly identically in both scenarios (Fig. 7 upper, Fig. 7 lower).

Overall, nature was equally well protected from agriculture in both scenarios. However, in the subsidy scenario, results came at an increasingly high cost (for society as a whole) compared to the fine scenario, for values greater than 1.5 (Fig. 6 left). Upon exceeding this value, the individual utility derived from land use in the subsidy- and fine scenarios diverged much faster. Therefore, subsidies were roughly equally cost effective up to this value, but overall fines are likely to have been the best option.

5.4.1.2. *Low Entrepreneurial Awareness and High Quality of Investment Climate (II)*
For "Low Entrepreneurial Awareness and High Quality of Investment Climate", state-centric governance setting II, comparing the subsidy scenario to the fine scenario showed that land uses were affected similarly in both scenarios (Fig. 3 right). However, identical levels of protection of nature were reached for lower values of subsidy, compared to values of fine. That is, the subsidy scenario achieved the same results as the fine scenario, only faster. This is also clearly reflected by the land-use patterns belonging to these scenarios (Fig. 8 upper, Fig. 8 lower). Although co-operation of farmers (Fig. 1) was equally strong in both scenarios, more farmers chose not to farm but to protect nature instead in the subsidy scenario. This led to a lower degree of fragmentation of agriculture (Fig. 8 lower). Furthermore, in the subsidy scenario, results came at an increasingly high cost (for society as a whole) compared to the fine scenario, for values greater than 1.79 (Fig. 5 right). Upon exceeding this value, the individual utility derived from land use in the subsidy- and fine scenarios diverged much faster. That is, subsidies could be acceptable up to this value in terms of cost effectiveness, but overall fines are likely to have been the best option.

5.4.1.3. *High Entrepreneurial Awareness and Low Quality of Investment Climate (III)*
For "High Entrepreneurial Awareness and Low Quality of Investment Climate", state-centric governance setting III, comparing the subsidy scenario to the fine scenario, showed that land uses were affected nearly identically in both scenarios (Fig. 4 left). Furthermore, that land-use patterns were affected nearly identically in both scenarios (Fig. 9 upper, Fig. 9 lower). Overall, nature was equally well protected from agriculture in both scenarios. However, in the subsidy scenario, results came at an increasingly high cost (for society as a whole) compared to the fine scenario, for values greater than 1.25 (Fig. 6 left). Upon exceeding this value, the individual utility derived from land use in the subsidy- and fine scenarios diverged much faster. Therefore, subsidies were roughly equally cost effective up to this value, but overall fines are likely to have been the best option.

5.4.1.4. *High Entrepreneurial Awareness and High Quality of Investment Climate (IV)*

For "High Entrepreneurial Awareness and High Quality of Investment Climate", state-centric governance setting IV, comparing the subsidy scenario to the fine scenario showed that land uses were affected similarly in both scenarios (Fig. 4 right). However, identical levels of protection of nature were reached for lower values of subsidy, compared to values of fine. That is, the subsidy scenario achieved the same results as the fine scenario, only faster. This is also clearly reflected by the land-use patterns belonging to these scenarios (Fig. 10 upper, Fig. 10 lower). Although co-operation of farmers (Fig. 1) was equally strong in both scenarios, more farmers chose not to farm but to protect nature instead in the subsidy scenario. This led to a lower degree of fragmentation of agriculture (Fig. 10 lower). Furthermore, in the subsidy scenario, results came at an increasingly high cost (for society as a whole) compared to the fine scenario, for values greater than 1.25 (Fig. 6 right). Upon exceeding this value, the individual utility derived from land use in the subsidy- and fine scenarios diverged much faster. That is, subsidies could be acceptable up to this value in terms of cost effectiveness, but overall fines are likely to have been the best option.

5.4.2. ***Between state-centric governance settings***

In this subsection, differences between state-centric governance settings were discussed, in an attempt to identify in which state-centric governance setting nature was protected best, given a specific policy instrument. That is, applying the same policy instrument to all state-centric governance settings, differences between state-centric governance settings were discussed (for both subsidy- and fine scenarios). However, differences between baselines of state-centric governance settings were discussed first, to identify in which state-centric governance setting nature was protected best without application of a policy instrument.

5.4.2.1. *Baselines*

Without any further measures of protection of nature, state-centric governance setting III, 'High Entrepreneurial Awareness and Low Quality of Investment Climate', worked out best for nature (Fig. 9 left, Fig. 11). State-centric governance setting IV, 'High Entrepreneurial Awareness and High Quality of Investment Climate', worked out second-best for nature (Fig. 10 left, Fig. 11). Furthermore, state-centric governance setting I, 'Low Entrepreneurial Awareness and Low Quality of Investment Climate', worked out second-worst for nature (Fig. 7 left, Fig. 11). While state-centric governance setting II, 'Low Entrepreneurial Awareness and High Quality of Investment Climate', worked out worst for nature (Fig. 8 left, Fig. 11). Clearly, the higher the quality of the investment climate the more protection of nature was required. Furthermore, the higher entrepreneurial awareness the less protection of nature was required. Consistently, the degree of co-operation (Fig. 1) and their effects on pattern formation were strongest in state-centric governance setting III (Fig. 9 left), and second-strongest in state-centric governance setting IV (Fig. 10 left). This suggests that the higher entrepreneurial awareness, the more farmers co-operated, and that co-operation is conducive to protection of nature. Moreover, that the lower the quality of investment climate given a high entrepreneurial awareness, the more farmers co-operated in a way that was even more conducive to protection of nature. In turn, this suggests that the lower entrepreneurial awareness, the less farmers co-operated and that this was not conducive to protection of nature (state-centric governance settings I and II). Moreover, that the higher the quality of the investment climate given a low entrepreneurial awareness (state-centric governance setting II), the more farmers behaved in a way that was even less conducive to protection of nature. Although this is not immediately clear from generated landscapes in state-centric governance settings I and II (Figs. 7–8), it is more than likely.

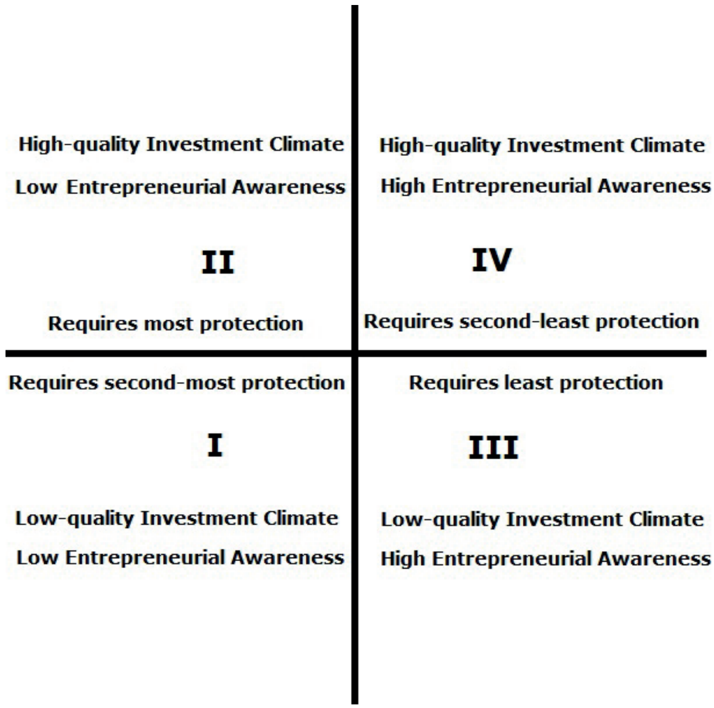

Fig. 11. The four state-centric governance settings and their required level of protection of nature, relative to one another.

5.4.2.2. *Top-down subsidy scenarios*

From comparing subsidy scenarios belonging to state-centric governance settings I and II, it was clear that protection of nature in subsidy scenario II was more effective than in subsidy scenario I, caused by a higher quality of the investment climate (Fig. 2, Fig. 3). This also caused an increased low-input agriculture in subsidy scenario II, compared to subsidy scenario I (Fig. 3). Given the low entrepreneurial awareness in subsidy scenarios I and II, co-operation between farmers (Fig. 1) was likely to be weak (Figs. 7–8 upper). This is the only case for which a higher quality of the investment climate caused a more effective protection of nature (not shown). Furthermore, from comparing subsidy scenarios belonging to state-centric governance settings II and III, it was clear that protection of nature in subsidy scenario III was more effective than in subsidy scenario II, caused by higher entrepreneurial awareness and a lower quality of the investment climate (Fig. 2, Figs. 3–4). Given the higher entrepreneurial awareness in subsidy scenario III, co-operation between farmers was likely to be weaker in subsidy scenario II (Figs. 8–9 upper). Moreover, given the lower quality of the investment climate in subsidy scenario III, farmers co-operated in a way that was even more conducive to protection of nature, compared to subsidy scenario II. Overall, low-input agriculture strongly decreased in subsidy scenario III, compared to subsidy scenario II (Figs. 3–4). That is, higher entrepreneurial awareness and a lower quality of the investment climate both caused low-input agriculture to decrease (Figs. 3–4). These comparisons imply that $\varepsilon_{I} < \varepsilon_{II} < \varepsilon_{III}$, with ε merely indicating how effectively nature was protected in the different state-centric governance settings, relative to one another.

From comparing subsidy scenarios belonging to state-centric governance settings II and IV, it was clear that protection of nature in subsidy scenario IV was more effective than in subsidy scenario II, caused by higher entrepreneurial awareness (Fig. 2, Figs. 3–4). This also caused a decreased low-input agriculture in subsidy scenario IV, compared to subsidy scenario II (Figs. 3–4). Given the higher entrepreneurial awareness in subsidy scenario IV, co-operation between farmers was likely to be weaker in subsidy scenario II (Fig. 8 upper, Fig. 10 upper). Furthermore, from comparing subsidy scenarios belonging to state-centric governance settings III and IV, it was clear that protection of nature in subsidy scenario III was more effective than in subsidy scenario IV, caused by a lower quality of the investment climate (Fig. 2, Fig. 4). This also caused a decreased low-input agriculture in subsidy scenario III, compared to subsidy scenario IV (Fig. 4). Given the high entrepreneurial awareness in subsidy scenarios III and IV, co-operation between farmers was likely to be strong (Figs. 9–10 upper). Moreover, given the lower quality of the investment climate in subsidy scenario III, farmers co-operated in a way that was even more conducive to protection of nature, compared to subsidy scenario IV. These comparisons imply that $\varepsilon_{II} < \varepsilon_{IV} < \varepsilon_{III}$. Because previous comparisons implied that $\varepsilon_{I} < \varepsilon_{II} < \varepsilon_{III}$, these two inequalities together imply that $\varepsilon_{I} < \varepsilon_{II} < \varepsilon_{IV} < \varepsilon_{III}$. That is, protection of nature was best in subsidy scenario III, second-best in subsidy scenario IV, second-worst in subsidy scenario II, and worst in subsidy scenario I, nearly consistent with baselines (Fig. 11), except for the switched order of subsidy scenarios I and II.

5.4.2.3. *Top-down fine scenarios*

From comparing fine scenarios belonging to state-centric governance settings I and II, it was clear that protection of nature in fine scenario I was more effective than in fine scenario II, caused by a lower quality of the investment climate (Fig. 2, Fig. 3). This also caused a decreased low-input agriculture in fine scenario II, compared to fine scenario I (Fig. 3). Given the low entrepreneurial awareness in fine scenarios I and II, co-operation between farmers (Fig. 1) was likely to be weak (Figs. 7–8 lower). Moreover, given the higher quality of the investment climate in subsidy scenario II, farmers behaved in a way that was even less conducive to protection of nature, compared to subsidy scenario I. Furthermore, from comparing fine scenarios belonging to state-centric governance settings I and III, it was clear that that protection of nature in fine scenario III was more effective than in fine scenario I, caused by higher entrepreneurial awareness (Fig. 2, Figs. 3–4). This also caused a decreased low-input agriculture in fine scenario I, compared to fine scenario III (Figs. 3–4). Given the higher entrepreneurial awareness in fine scenario III, co-operation between farmers was likely to be weaker in fine scenario I (Fig. 7 lower, Fig. 9 lower). These comparisons imply that $\varepsilon_{II} < \varepsilon_{I} < \varepsilon_{III}$, with merely indicating how effectively nature was protected in the different state-centric governance settings, relative to one another.

From comparing fine scenarios belonging to state-centric governance settings III and IV, it was clear that protection of nature in fine scenario III was more effective than in fine scenario IV, caused by a lower quality of the investment climate (Fig. 2, Fig. 4). This also caused a decreased low-input agriculture in fine scenario III, compared to fine scenario IV (Fig. 4). Given the high entrepreneurial awareness in fine scenarios III and IV, co-operation between farmers was likely to be strong (Figs. 9–10 lower). Moreover, given the lower quality of the investment climate in fine scenario III, farmers co-operated in a way that was even more conducive to protection of nature, compared to fine scenario IV. Furthermore, from comparing fine scenarios belonging to state-centric governance settings I and IV, it was clear that protection of nature in fine scenario IV was more effective than in fine scenario I, caused by higher entrepreneurial awareness and a higher quality of the investment climate (Fig. 2, Figs. 3–4). Given the higher entrepreneurial awareness in fine scenario IV, co-operation between farmers was likely to be weaker in fine scenario I (Fig. 7 lower, Fig. 10 lower). Conversely, a higher quality of the investment climate had a negative effect on protection of nature. Overall, low-input agriculture did not change noticeably, i.e.,, changes caused by higher entrepreneurial awareness and a higher quality of the investment climate were offset (Figs. 3–4). These comparisons imply that $\varepsilon_{I} < \varepsilon_{IV} < \varepsilon_{III}$. Because previous comparisons implied that $\varepsilon_{II} < \varepsilon_{I} < \varepsilon_{III}$, these two inequalities together imply that $\varepsilon_{II} < \varepsilon_{I} < \varepsilon_{III}$. That is, protection of nature was best in fine scenario III, second-best in fine scenario IV, second worst in fine scenario I, and worst in fine scenario II, consistent with baselines (Fig. 11).

5.5. Conclusions

For all state-centric governance settings, a fine was likely to be the most cost-effective policy instrument for protection of nature, rather than a subsidy. For state-centric governance settings II (“Low Entrepreneurial Awareness and High Quality of Investment Climate”) and IV (High Entrepreneurial Awareness and High Quality of Investment Climate”), co-operation of farmers and its effect on pattern formation were more dominant when a fine was applied. Comparing state-centric governance settings subjected to neither a subsidy nor a fine (i.e.,, baselines), the most effective- and second-most effective protection of nature were generated under state-centric governance settings III (“High Entrepreneurial Awareness and Low Quality of Investment Climate”) and IV, respectively. The higher entrepreneurial awareness, the less protection of nature was required because more farmers co-operated, which was more conducive to protection of nature. The higher the quality of the investment climate, the more protection of nature was required because less farmers co-operated, which was less conducive to protection of nature. Comparing state-centric governance settings identically subjected to a subsidy, the most effective- and second-most effective protection of nature were generated under state-centric governance settings III and IV, respectively. Comparing state-centric governance settings identically subjected to a fine, the most effective- and second-most effective protection of nature were again generated under state-centric governance setting III and IV, respectively. Consistently, the most (cost-)effective protection of nature was produced when a fine was applied in state-centric governance setting III, because farmers co-operated in a way that was most conducive to protection of nature.

Once more into the darkness,
Until first light hits,
Into the pitch black burning,
That cleanses our spirits.

6

Synthesis

Synthesis

In this chapter, it is discussed whether—and if so, to what extent—the research questions posed in the general introduction of this thesis could be answered by the applied empirical-statistical- and process-based modeling approaches. In addition, the value added by viewing separate research findings together is discussed, and how these different approaches dealt with the real-world complexity of chosen land-use change processes.

6.1. Ways of including governance into land-use modeling

6.1.1. *Empirical-statistical modeling*

Quantification of socially constructed perceptions of governance is required to allow for a semi-positivistic approach to the modeling of governance in the context of land use (*1.1.2.2.1. Empirical-statistical modeling*). Because the World Bank dimensions of governance (repeated in Table 1) represent quantifications of socially constructed perceptions of "State-centric governance" (*1.1.2.1. Governance*), these dimensions can be used for precisely such an approach. That is, these can be incorporated into an empirical-statistical model of how state-centric governance relates to arable-agricultural expansion- and/or intensification, and dominant spatiotemporal processes of fragmentation and expansion of nature. Evidently, the real-world complexity of governance processes cannot be entirely captured by a mere number of six general dimensions designed to be comparable across countries at the national level, as these are far too abstract to account for details specific to (sub)national land-use planning processes. On the one hand, the higher the level of abstraction, the less statistical relationships can be linked to real-world processes in an empirically specific way, as the number and complexity of processes that could explain them grow beyond our ability to disentangle and comprehend. Clearly, any results of statistical analyses involving the World Bank dimensions of governance cannot be interpreted in the sense of their exact definitions (Table 1), as these are far too delicate and complex to be incorporated in crude statistical analyses. Furthermore, the separate World Bank dimensions are highly correlated between themselves (not shown), further preventing meaningful interpretation in this sense. On the other hand, their high degree of abstraction does allow for general and meaningful interpretation of statistical relationships between these crude estimates of quality of governance and those of arable-agricultural expansion- and/or intensification and dominant spatiotemporal processes of fragmentation and expansion of nature, at an aggregate level, which would otherwise not have been possible. That is, the higher the empirical specificity, the more geographically restricted the validity of any statistical inferences would be.

Table 1. The World Bank dimensions of governance.

Dimension	Definition
Voice and accountability	Measures the public perception of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.
Government effectiveness	Measures the public perception of the quality of public- and civil services, the degree of independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.
Regulatory quality	Measures the public perception of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.
Rule of law	Measures the public perception of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.
Control of corruption	Measures the public perception of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.
Political stability and the absence of violence	Measures the public perception of the likelihood of destabilization or overthrowing of a government by unconstitutional or violent means, leading to domestic violence and terrorism.

Source: World Bank, http://info.worldbank.org/governance/wgi/index.aspx#home.

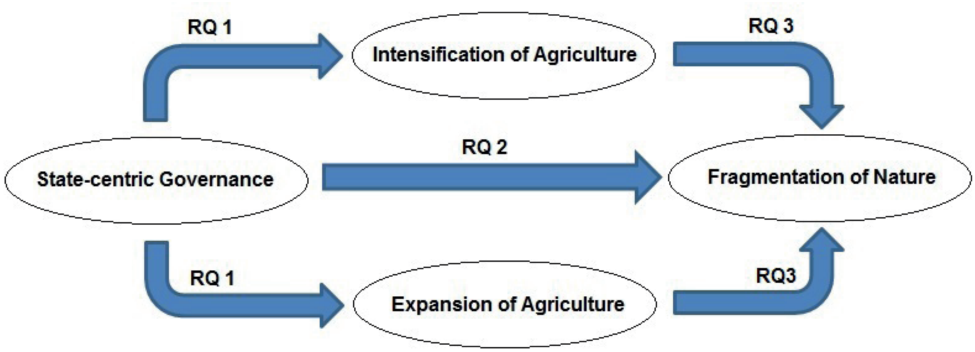

Fig. 1. Schematic illustration of empirical-statistical research questions (RQs).

6.1.1.1. *Research question 1*
Does state-centric governance directly drive—and if so, how—expansion and/or intensification of arable agriculture?

The analysis in chapter 2 demonstrates that quality of state-centric governance in countries where agricultural area expands differs significantly from that in countries where the agricultural area contracts, measured over 173 countries across the globe for 1975–2007. On the one hand, less well-developed countries score lower on quality of state-centric governance (*2.3.1. Between-groups analysis*, Fig. 2, Table 2), while there it is more important to the explanation of spatial variability in area increase (*2.3.2. Within-groups analysis,* Table 3). These countries are consistently primarily associated with "growth" behavior, i.e., behavior characterized by expansion of arable agriculture and increasing yield per unit area (*2.3.1. Between-groups analysis,* Fig. 1). On the other hand, more-developed countries score higher on quality of state-centric governance (*2.3.1. Between-groups analysis*, Fig. 2, Table 2), while there it is more important to the explanation of spatial variability in yield increase (*2.3.2. Within-groups analysis,* Table 3). These countries are consistently primarily associated with "intensifying" behavior, i.e., behavior characterized by contraction of arable agriculture and increasing yield per unit area (*2.3.1. Between-groups analysis,* Fig. 1). This indicates that governance is more related to expansion in case of "growth" behavior, and more to intensification in case of "intensifying" behavior. The analysis performed in chapter 2 further suggests that across the globe, countries with lower scores of quality of governance are more likely to achieve a production increase by means of area expansion rather than by means of yield increase. Moreover, as quality of governance improves, this orientation toward production tends to flip from expansion toward intensification.

Yields were found to be significantly higher in countries with more political rights and civil liberties (Fulginiti et al., 2004), indicating that the dimension "Voice and accountability" is positively related to yield increase (Table 1). Infrastructure plays a key role in the realization of agricultural potential of remote rural areas, while governmental agricultural research & development programs play a key role in increasing yields (Thirtle et al., 2003). The quality of these public goods and services, measured by the dimension "Government effectiveness", is therefore also likely to be positively related to agricultural development (yield increase). Countries with poor "Regulatory quality" tend to implement policies that result in high taxation of agriculture, which has negative effects on private-sector development- and investment (Krueger et al., 1991). For example, advances in agricultural development become unlikely, as these advances strongly depend on private investments in agricultural research and development (Thirtle et al., 2003), which are not likely to be made when investors cannot be assured of future revenues. Furthermore, failing enforcement of property rights caused by poor “Rule of law” would also add to a negative perception of the investment climate through higher levels of instability and uncertainty, negatively affecting agricultural development. It has been suggested that large fertilizer producers persuaded African governments to impose particular fertilization programs upon farmers through bribery and other forms of corruption (World Bank, 2010), despite the fact that farmers often knew more about the particular deficits of their soils, having a negative effect on agricultural development through lack of “Control of corruption”. In countries facing higher levels of political conflict and war, yields were reported to be significantly lower (Fulginiti et al., 2004), suggesting that “Political stability and the absence of violence” is positively related to agricultural development (yield increase). Overall, higher scores of quality of state-centric governance are more likely to drive the intensification of arable agriculture, while lower scores of quality of state-centric governance are more likely to drive the practicing of cheaper forms of arable agriculture, requiring less financial investment to keep up with the growing demand for food. In particular, expansion at the expense of nature, which is common in developing countries where nature is often abundant yet poorly protected (Kakonge, 1998).

6.1.1.2. *Research question 2*

Does state-centric governance directly drive—and if so, how—dominant spatiotemporal processes of fragmentation of nature?

The analysis presented in chapter 3 reveals four dominant spatiotemporal processes of change in nature (*3.2.2. Methods*, Fig. 2), by capturing past developments in two indicators: overall change in nature area and change in average patch size of nature, measured over 20 European countries (*3.2.1. Data*, Fig. 1) for 1990–2006. The analysis demonstrates that nature expansion was positively related to overall quality of state-centric governance for this period (*3.3. Results,* Fig. 4, Table 5). Nature area increased in a small majority of European countries (*3.3. Results,* Fig. 3), but this is not necessarily the result of deliberate nature restoration alone. New nature also developed on abandoned agricultural land, which is not necessarily a positive development in terms of biodiversity. Remarkably, patch size increased in countries with poorer state-centric governance while it decreased in countries with better state-centric governance (*3.3. Results,* Fig. 4, Table 5), for which there is more than one possible explanation. One possible explanation is that increasing patch size may be associated with land abandonment, which may in turn be associated with poor governance.

This is consistent with the occurrence of considerable abandonment of grasslands, due to major land reforms designed to privatize agricultural land in the CEECs after the fall of the iron curtain, particularly at the boundaries of agricultural and nature areas (Kuemmerle et al., 2006; Hobbs and Cramer, 2007; Bakker et al., 2011). Another explanation is that compulsory purchase of land for the development of nature is easier in countries with poor governance, possibly allowing for more efficient implementation of ecological networks.

Nature needs to be protected from overexploitation by private parties, possibly resulting in removal, shrinkage, or fragmentation of nature through the government's capacities for effective formulation and implementation of policies and regulations. Because these capacities are measured by "Government effectiveness" (Table 1), this dimension is likely to be negatively related to such removal, shrinkage, or fragmentation. Moreover, the extent to which these policies and regulations are properly enforced by law-enforcement agencies, measured by "Rule of law", is therefore also likely to be negatively related to such removal, shrinkage, or fragmentation. Once policies and regulations have been formulated, implemented, and enforced, yet are of insufficient "Regulatory quality", private parties may still overexploit nature. Furthermore, the extent to which officials are prone to temptations such as bribery and abusing their position and role by privileging specific private interests that will erode existing nature and harm the functioning of ecosystems, such as clearance for property development or illegal harvesting of wood, is measured by "Control of corruption". Therefore, "Regulatory quality" and "Control of corruption" are also likely to be negatively related to removal, shrinkage, or fragmentation of nature. On the other hand, the greater the degree to which citizens are allowed to affect decision making through democratic voting processes, measured by "Voice and accountability", the more likely the realization of formation, expansion, or connection of nature (Jones-Walters et al., 2009). The "Political stability and the absence of violence" dimension was excluded from the analysis, because there was no political instability leading to civil unrest or violence in the European countries included into the analysis during the period of study. As mentioned earlier (*6.1.1. Empirical-statistical modeling*), any results of statistical analyses involving the World Bank dimensions of governance cannot be interpreted in the sense of their exact definitions (Table 1), as these are far too delicate and complex to be incorporated in crude statistical analyses. Furthermore, the separate World Bank dimensions are highly correlated between themselves (not shown), further preventing meaningful interpretation in this sense. Precisely because of this, however, a crude yet credible indicator of overall quality of governance could be constructed in which the influence of all the separate five dimensions was equally represented (*3.2.1. Data*, Table 3), through Principal Component Analysis (PCA).

Generally, lower scores of overall quality of state-centric governance are more likely to drive the processes of removal, shrinkage, and dissection of nature through changes in nature area (*3.3. Results,* Figs. 3–4, Table 5). Higher scores of overall quality of state-centric governance are more likely to drive the processes of formation, expansion, and connection of nature through changes in both nature area and patch size (*3.3. Results,* Figs. 3–4, Table 5). Although the data available for this research did not allow for analysis beyond the European level of geographical spatial scale, this approach may also be useful globally for reporting to the Convention on Biological Diversity (CBD) in 2020. That is, to give general trends in land cover and fragmentation and their potential relationships to state-centric governance.

6.1.1.3. *Research question 3*

If state-centric governance drives expansion and/or intensification of arable agriculture directly, does it also drive—and if so, how—processes of fragmentation of nature through these processes?

From the data used for the analysis presented in chapter 2, it is known that the countries analyzed in chapter 3 were predominantly "intensifying" countries. That is, Austria, Belgium-Luxembourg, Denmark, Germany, Hungary, Ireland, Italy, the Netherlands, Poland, Portugal, Romania, and Spain were "intensifying" countries over 1975–2007 (*2.3.1. Between-groups analysis,* Fig. 2), while there were no—separate—data available for Estonia, Latvia, Lithuania, and Slovenia. Bulgaria is the only country known to have been a "decline" country over this period, i.e., behavior characterized by contraction of arable agriculture and decreasing yield per unit area, while France is the only country that qualified as a "growth" country (*2.3.1. Between-groups analysis,* Fig. 2). However, the increase in agricultural area was negligible for France, making it more inclined toward "intensifying" behavior; consistent with what one might expect for a western European country such as France. Although "intensifying" behavior was clearly dominant among these countries, lower scores of quality of state-centric governance could still be more likely to drive the process of expansion of agriculture, while higher scores of quality of state-centric governance could still be more likely to drive the process of intensification (*6.1.1.1. Research question 1*). Furthermore, lower scores of quality of state-centric governance are more likely to drive the processes of removal, shrinkage, and dissection of nature, while higher scores of quality of state-centric governance are more likely to drive the process of formation, expansion, and connection of nature (*6.1.1.2. Research question 2*). These relationships have been established for different periods using slightly different methods. That is, those presented in chapter 2 hold across the globe for 1975–2007, while those presented in chapter 3 only hold across Europe for 1990–2006. Furthermore, the former relationships were established using control indicators, which was not possible for the latter due to an insufficient number of countries (i.e., only 20 countries could be used compared to 173 for the global analysis). The World Bank governance dimensions also were not used in the same way for these studies. Multivariate-regression analysis was applied on separate indicators in chapter 2, while PCA was applied to construct an overall indicator of state-centric governance in chapter 3. That is, to resolve the issue of insufficient observations for multivariate-regression analysis, PCA was used to allow for reliable bivariate-regression analysis instead. Despite their—minor—methodological dissimilarities, chapters 2–3 do give rise to plausible interpretations of their combined results.

On the one hand, these results may imply that increased inclination toward expansion of agriculture could be commensurate with increased removal, shrinkage, and dissection of nature (i.e., negative change in nature area). Although tempting, the negative changes in nature area may not be assumed to be entirely attributable to changes in agricultural area alone. That is, for all countries with a negative change in nature area except three, changes in nature area could also be entirely attributable to changes in urban area alone (not shown). For two of the three countries for which this is not the case—Lithuania and Romania—the greater parts of the observed changes in nature area could possibly be explained by changes in agricultural area (not shown). For the remaining country—Bulgaria—only a small part of the observed change in nature area may possibly be explained by changes in agricultural area (not shown). On the other hand, these results may imply that increased inclination toward intensification of agriculture could be commensurate with increased formation, expansion, and connection of nature (i.e., positive change in nature area). Overall, the combined results of chapters 2–3 seem consistent with the finding that lower scores of quality of state-centric governance are more likely to drive the practicing of cheaper forms of arable agriculture (*6.1.1.1. Research question 1*), requiring less financial investment to keep up with the growing demand for food. In particular, expansion at the expense of nature, which is common in developing countries where nature is often abundant yet poorly protected (Kakonge, 1998).

Furthermore, combined results suggest that increased inclination toward intensification of agriculture could be more commensurate with increased formation of smaller-than-average patches of nature (i.e., positive and negative change in nature area and average patch size, respectively). However, the latter would imply that increased inclination toward expansion of agriculture could be more commensurate with increased formation of larger-than-average patches, expansion, and connection of nature (i.e., positive change in both nature area and average patch size). Clearly, the implication that increased inclination toward expansion of agriculture might go hand in hand with improved structural connectivity of nature could represent a contradiction. Moreover, privatization of land, through broad agricultural reforms that were the dominant drivers of land-use change in the Central- and Eastern European Countries (CEECs) located in the upper-right quadrant of the characterization of dominant spatiotemporal processes (*3.3. Results,* Fig. 3), has led to large-scale abandonment of agricultural land (Hobbs and Cramer, 2007). Therefore, it is likely that abandonment of agricultural land—and its effect on land cover—was often mistakenly recorded as a positive change in nature area for these countries. This is consistent with the explanation that increasing patch size could be commensurate with a greater degree of abandonment, i.e., for the apparently counterintuitive relationship between state-centric governance and change in average patch size (*3.3. Results,* Fig. 4, Table 5). Overall, it is less likely that formation of new patches and/or corridors of nature significantly contributed to structural-connectivity increases in these countries compared to e.g., Austria, Denmark, Germany, Ireland, and the Netherlands (Mandemaker et al., 2013).

Countries located in the upper half of the characterization of dominant spatiotemporal processes (*3.3. Results,* Fig. 3) typically still have large areas of forest, while those in the lower half have suffered considerable to severe fragmentation of nature (Mandemaker et al., 2013). Furthermore, in countries with large areas of forest, farmers are known to behave in a classical Thünian way (De Groot, 2003). That is, they display frontier behavior based on positive feedbacks of growth between income, urban demand, agriculture, and extraction of natural resources and deforestation, while in countries with highly fragmented nature resulting from such frontier behavior, farmers are known to display immiserization behavior (De Groot, 2003). That is, frontier behavior tends to occur more in growing agricultural economies—e.g., the "growth" countries of chapter 2—that have yet to complete the transition into a service-based economy. While the latter type of economy often suffers from possible side effects of such a transition (e.g., fragmentation of nature). Instead of nature consumption at extraction frontiers, which have usually all but disappeared in such countries, remnants of nature are often at risk of being converted into agriculture. The lower farmers' income the less means will be available for intensification of existing agricultural land, and the higher the risk of conversion of such remnants through expansion of existing agricultural land, which is a known characteristic of immiserization behavior (De Groot, 2003). As there is a clear relation between quality of governance and farmers' income and stability (FAO 2009a, 2009b; IAASTD, 2009), it is likely that farmers’ income is lower in countries in the lower-left- and upper-right quadrants compared to those in the lower-right quadrant (where quality of governance is highest). Therefore, the found significant relationship between quality of governance and change in nature area for the lower-left- and right quadrants of the characterization of dominant spatiotemporal processes (*3.3. Results,* Fig. 4, Table 5), may imply that immiserization behavior increased with lower quality of governance and increasingly negative change in nature area. That is, compared to countries with highly fragmented nature but relatively wealthy farmers such as Germany or the Netherlands (Mandemaker et al., 2013), where immiserization is far more unlikely to occur, also owing to better protection of nature. This is consistent with the result that increased inclination toward expansion of agriculture might be commensurate with increased removal, shrinkage, and dissection of nature, which was made apparent by combining the results of chapters 2–3. Should causal relationships be assumed, it is possible that poorer and better state-centric governance directly driving expansion and intensification of agriculture, also indirectly drive fragmentation of nature to a greater and lesser degree, respectively. That is, expansion of agricultural land in countries with already highly fragmented nature areas through immiserization, is likely to be more harmful to nature areas than intensification of already existing agricultural land.

6.1.2. *Process-based modeling*

By defining spatial and temporal units of analysis suitable to changes in agricultural land use for a particular study area, land-use changes may be recorded for each patch of land in this study area for each temporal observation, with the total number of patches determined by the chosen spatial resolution. If such changes are recorded over a sufficient amount of time, it should be possible to deduce what the systematic land-use changes were throughout the study area. That is, by calculation of the frequencies of specific land-use transitions for each patch of land in the study area, with the total number of patches determined by the chosen spatial resolution. If changes are monitored sufficiently long for random transitions to average out, the obtained frequencies should represent systematic change induced by human preference (rational or not). Furthermore, the systematic behavior and human preferences indicated by these—local—frequencies should also be reflected by the aggregate land-use pattern formed by individual decision-making. Therefore, it should be possible to link locally observed land-use change to aggregate land-use patterns, through studying the effects of modeled human behavior on simulated land-use patterns. In chapters 4–5 of this thesis, human behavior was assumed to be driven by a utility maximization rationale modeled by a multinomial-choice model. A conceptualization of individual decision-making processes was operationalized through a set of specific land-use transitions occurring with spatially varying probabilities. In turn, these probabilities were determined by the human preferences modeled by the multinomial-choice model introduced in chapter 4, based on the utility that is perceived to be gained from making specific land-use transitions. Utility was entirely identified with income in chapters 4–5, but real-world utility may also be gained through behavior based on non-monetary motivations. Although the proposed way of gathering local land-use data for a particular study area should be able to detect such subjective, yet still systematic decision-making, modeling this behavior would be beyond the scope of the agricultural model written for this research. Moreover, for agricultural land-use systems, economic rationales are known to be the major determinants of observed systematic behavior (IFPRI, 2006; FAO 2009c).

6.1.2.1. *Research question 4*
Is it possible—and if so, how—to systematically and verifiably approximate real-world dynamic complexity of agricultural land-use systems and their governance with a Pattern-Oriented Modeling (POM) approach based on individual decision-making processes?

Given that conceptualizations of decision-making and other mechanisms controlling behavioral and environmental constraints would approach those of a real-world study area sufficiently close, and that land-use change data of this study area would permit identification of the degree and composition of systematic influence on aggregate land-use patterns, meaningful comparison of empirical and simulated spatial statistics should be possible. Furthermore, it should be possible to approximate real-world land-use patterns with simulated ones, by minimizing differences between real-world- and simulated spatial statistics. These differences could be minimized by applying modeled mechanisms in a systematic way, iteratively comparing real-world- and simulated land-use patterns and making systematic adjustments to explore which mechanisms and settings deliver optimal results (i.e., by following the POM approach). To this purpose, a spatial statistic was proposed in chapter 4 of this thesis, based on the aggregate uncertainty associated with agricultural land-use systems that emerges from local transition probabilities: the transition entropy (*4.3.4. Aggregate uncertainty,* Eq. 1). The more systematic decision-making occurs, the lower the transition entropy of the aggregate landscape will be. That is, when farmers take only utility maximizing decisions, the aggregate landscape will be least random and its entropy minimized. Conversely, when farmers take no utility maximizing decisions at all, the aggregate landscape will be most random and its entropy maximized. In this sense, the chosen way of modeling farmers' behavior resembles the modeling of ideal-gas behavior in thermodynamics. That is, the entropy of an ideal gas in a state of equilibrium is always maximized, calculated over the possible states of gas particles. Analogously, in this thesis the entropy of a landscape is calculated over the possible land-use states of landscape units, through local transition probabilities associated with these land-use states. The entropies of landscapes that are "ideal" in the thermodynamic sense will be constant over time. However, this is not the case for landscapes that are shaped by systematic behavior. For such landscapes, the entropy and spatial distribution of land-use states may significantly vary over time until a state of statistical equilibrium is reached, while such states are generally characterized by small dynamic fluctuations (after stabilization). Therefore, the history of the landscape should be taken into account when determining the system-state variables associated with a particular state of statistical equilibrium. That is, by calculating the average values of these variables over a period of time that ensures a negligible deviation from averages that would have been calculated over an infinite period of time.

6.1.3. *Comparing empirical-statistical- and process-based modeling*

The semi-positivistic empirical-statistical and positivistic process-based modeling approaches to governance applied in this thesis are constrained by the same real-world complexity. However, where empirical-statistical methods merely provide us with the ability to *cope* with real-world complexity when sufficient process-based information is unavailable, process-based methods provide us with the ability to attempt verifiable *incorporation* of real-world complexity. The second and third chapters of this thesis attempted to capture the real-world complexity of nature-agriculture interactions by empirical-statistical means, while in the fourth and fifth chapters of this thesis verifiable incorporation of this real-world complexity was attempted through Pattern-Oriented Modeling (POM) based on individual decision-making processes (Grimm et al., 2005, 2006). The challenge posed by a positivistic approach to the modeling of governance and individual decision-making processes is how to address the overall insufficient availability of process-based information, so that minimal amounts of available or measureable local land-use change information could still be linked to aggregate patterns of land use in a meaningful and verifiable way (Parker et al., 2008a, 2008b).

In chapters 4–5, the rationality parameter determines to what extent available information can be exploited by farmers to maximize utility, while the anticipation parameter determines how much—future—information is available for farmers to exploit. The ability of real-world farmers to process information on which they base land-use decisions is known to be related to general education and governmental educational programs designed to raise farmers' entrepreneurial awareness (IFPRI, 2006; FAO 2009c; IAASTD, 2009). Therefore, it was assumed that the higher farmers' entrepreneurial awareness, the more rational their land-use decisions will be. That is, the rationality parameter was assumed to model farmers' entrepreneurial awareness. In turn, the general level and quality of education and the ability to actually take preferred decisions depend on "Government effectiveness", responsible for the delivery of such public services (Table 1). The rationality parameter could thus be interpreted to indirectly reflect the quality of this dimension of governance. Furthermore, for farmers to anticipate on projections of future revenue and invest in intensification, confidence in the resilience and stability of the investment climate is required (IFPRI, 2006; FAO 2009c; IAASTD, 2009). The higher the quality of the investment climate the more and further farmers are assumed to anticipate on these projections, modeled by a higher value of the anticipation parameter. In turn, the quality of the investment climate depends on "Regulatory quality", responsible for the promotion of private-sector development (Table 1). The anticipation parameter could thus be interpreted to indirectly reflect the quality of this dimension of governance.

In chapter 4, resulting emergent behavior could sometimes be interpreted as intensification of agriculture (*4.5.4. Intensification*). That is, when the quality of the investment climate was high, emergent behavior that resulted from an increasing entrepreneurial awareness could be interpreted as intensification, but not when the quality of the investment climate was low. Furthermore, in a high-quality investment climate, two types of intensification could be identified: intensification through yield increase per unit area and through substitution of land for inputs. A transition from the former to the latter type of intensification was observed with increasing entrepreneurial awareness. If farmers did not participate in the sharing of costs through forming co-operatives, this transition occurred for lower values of entrepreneurial awareness compared to when they did participate in the sharing of costs. That is, sharing of costs causes yield increase per unit area to be the more dominant type of intensification in the model. Overall, this could imply that when "Regulatory quality" is sufficiently high to allow for a high-quality investment climate, intensification is facilitated by sufficiently high quality of "Government effectiveness". This is consistent with the main result of chapter 2 stating that higher quality of governance is more likely to drive intensification than expansion. Furthermore, that intensification through yield increase per unit area is associated with a slightly lower quality of governance than intensification through substitution of land for inputs (*4.5.4. Intensification*) is consistent with the differences in production behavior of the "Growth" and "Intensifying" countries of chapter 2, respectively (*2.3.1. Between-groups analysis*).
In chapter 5, it was shown that high entrepreneurial awareness combined with a low-quality investment climate worked out best for nature (*5.4.2. Between state-centric governance settings*, Fig.11, Setting III). That is, nature required the least protection from farmers under these conditions. Furthermore, overall, nature was shown to be protected most effective by

applying fines for reclamation of land in a natural state for agricultural purposes, compared to subsidizing the use of land in a natural state. However, in the model, intensification is known to occur for high entrepreneurial awareness combined with a high-quality investment climate (*5.4.2. Between state-centric governance settings*, Fig. 11, Setting IV); the same model-parameter values were applied in chapter 5 as in chapter 4. Moreover, nature required the second-least protection from farmers under these conditions. Therefore, nature could still be very well protected under these conditions, while at the same time the potential for agricultural intensification might also be realized by increasing entrepreneurial awareness, facilitated by a high-quality investment climate. Again, entrepreneurial awareness and quality of the investment climate might in turn be facilitated by "Government effectiveness" and "Regulatory quality", respectively (Table 1). Furthermore, the observed land-use patterns for setting IV (*5.3.2. Land-use patterns*, Fig. 10) show that application of fines results in overprotection of nature and marginalization of agriculture less easily than subsidies. This difference is not observed for the patterns generated by setting III (*5.3.2. Land-use patterns*, Fig. 9).

6.2. Key conclusions

- Governance can be meaningfully included into land-use modeling in both semi-positivistic (i.e., empirical-statistical) and positivistic (i.e., process-based) ways
- The empirical-statistical result that occurrence of agricultural intensification is likely to be more commensurate with higher quality of governance can be reproduced as an emergent property of aggregated individual behavior of farmers constrained by state-centric governance, through abstract process-based simulation (pattern-oriented modeling) of spatially explicit agricultural land-use systems
- The empirical-statistical result that better protection of nature is likely to be commensurate with higher quality of governance can be reproduced as emergent properties of aggregated individual behavior of farmers in different policy scenarios, through abstract process-based simulation (pattern-oriented modeling) of spatially explicit agricultural land-use systems
- Abstract process-based simulation (pattern-oriented modeling) of spatially explicit agricultural land-use systems allows for identification of different and verifiable governance conditions and policy strategies regarding protection of nature
- Abstract process-based simulation (pattern-oriented modeling) of spatially explicit agricultural land-use systems allows for identification of the optimal verifiable optimal governance conditions and policy strategy for protection of nature and the economic interests of farmers in agricultural land-use systems

6.2.1. *Recommendations for further research*

In this thesis, it has been shown that governance can be meaningfully included into land-use modeling in both semi-positivistic (i.e., empirical-statistical) and positivistic (i.e., process-based) ways. However, the relationship between empirical specificity and degree of abstraction has not been addressed. Fig. 2 shows a conceptual representation of land-use models, characterized by empirical specificity and degree of abstraction. Every point on the circular curve represents a different model. The curve is circular to represent that all land-use models on it are equally valuable in their own right, although characterized by different empirical specificities and degrees of abstraction. However, different combinations of empirical specificity and degree of abstraction, i.e., different models, describe the same real-world complexity differently.

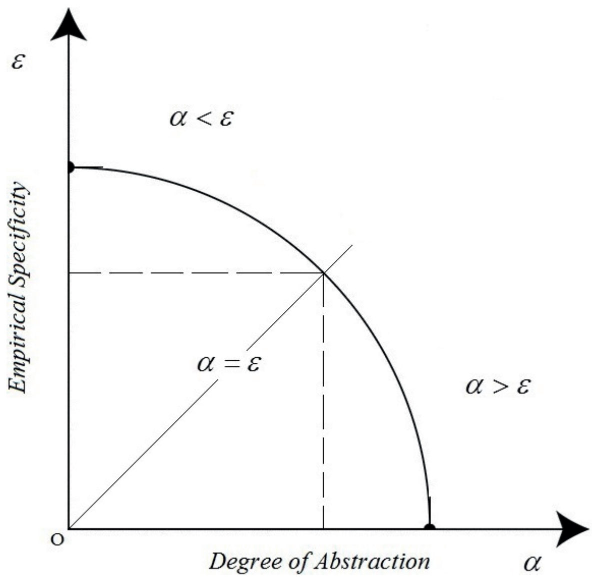

Fig. 2. Conceptual representation of land-use models characterized by empirical specificity and degree of abstraction.

According to this representation (Fig. 2), there are three main classes of land-use models, each characterized by a different way of describing the same real-world complexity. There are those models that more empirically specific than abstract ($\alpha < \varepsilon$), indicating the more and more empirical-statistical model, to the extreme of overly empirical models ($\alpha \rightarrow 0$). In case of the latter extreme, there is a wealth of information allowing for empirical validation, but key processes cannot be sufficiently captured by empirical-statistical relationships. That is, despite all the information available, there is no predictability beyond the variance and other statistical properties of model output (i.e., compared to real-world data). Furthermore, there are those models that are more abstract than empirically specific ($\alpha > \varepsilon$), to the extreme of oversimplification ($\varepsilon \rightarrow 0$). In case of this extreme, all is predictable in theory, but in practice, chosen variables and theorized relationships prove unverifiable because there is simply no way of empirical validation. However, if a model of a real-world land-use system could optimize the empirical specificity with which this model can be validated and the degree of generality to which this system can be understood, then its predictive power might be maximized. That is, the class of models for which empirical specificity is equal to the degree of abstraction ($\alpha = \varepsilon$) might represent a class of models for which predictive power is potentially maximal. If so, these models would be most suited to describe the real-world complexity encountered in land-use systems.

However, the research in this thesis suggests there is still a considerable gap between the empirical-statistical models ($\alpha < \varepsilon$) and the developed pattern-oriented model ($\alpha > \varepsilon$) used for the inclusion of governance into land-use modeling. Therefore, it is recommended that research efforts be devoted to the development of models that further reduce the gap between empirical specificity and degree of abstraction, that is ($\alpha - \varepsilon$) $\rightarrow 0$. Moreover, to apply and validate such models successfully, large amounts of data would be required that are currently unavailable. This is why even more research efforts should be devoted to the development of high-resolution monitoring systems of land-use change, to allow for larger and better databases.

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Summary

Summary

An improved understanding of complex processes of both socio-political and economic governance may help to abate negative effects of increasing pressures of rising global food demand and agricultural land use on nature. Therefore, in this thesis, relationships between governance, agriculture, and nature were quantified, and it was investigated to what extent governance can be meaningfully included into land-use modeling. As outlined in the general introduction of this thesis, two main approaches to the inclusion of governance were distinguished: a semi-positivistic empirical-statistical approach and a positivistic process-based approach. Therefore, this thesis consists of two parts: one that includes governance through empirical-statistical modeling, and one that includes governance through process-based modeling.

In the first part of this thesis (chapters 2–3), relationships between quantified perceptions of state-centric governance, arable agriculture, and nature were identified through semi-positivistic empirical-statistical approaches. To investigate whether state-centric governance directly drives—and if so, how—expansion and/or intensification of arable agriculture at the global level (chapter 2), empirical-statistical relationships between agricultural production dynamics and state-centric governance indicators were identified for 173 countries between 1975 and 2007. Four groups of countries were distinguished: those with both area and yield increases ("growth" countries); those with increasing yields but decreasing area ("intensifying" countries); those with decreasing yields but a growing area ("expansion" countries); and those with both declines in yields and area ("decline" countries). Differences between these four groups were analyzed, and also governance-production relationships within these groups. The analysis of governance-production relationships within the four groups suggests that countries with a lower quality of governance are more inclined to achieve production increases by expanding agricultural area rather than increasing yields. Moreover, as quality of governance becomes higher, this orientation of countries towards production tends to flip from expansion towards intensification. Overall, higher quality of state-centric governance is more likely to drive the intensification of arable agriculture, while lower quality of state-centric governance is more likely to drive the practicing of cheaper forms of arable agriculture, requiring less financial investment to keep up with the growing demand for food.

To investigate whether state-centric governance directly drives—and if so, how—dominant spatiotemporal processes of fragmentation and expansion of nature, empirical-statistical relationships between overall quality of state-centric governance and such processes were identified through cross-national comparison for 20 European countries for the period 1990–2006 (chapter 3). Land-cover change trends were detected by comparing CORINE land-cover maps from the years 1990 and 2006. Dominant spatiotemporal processes of change in nature were characterized by capturing past developments in two indicators: overall change in nature area and change in average patch size of nature. This resulted in four different dominant spatiotemporal processes of structural change: "Formation of larger-than-average patches of nature and/or Expansion of nature and/or Connection of nature"; "Formation of smaller-than-average patches of nature"; "Removal of smaller-than-average patches of nature"; and "Removal of larger-than-average patches of nature and/or Shrinkage of nature and/or Dissection of nature". The majority of countries expanded their total nature, although this is likely not to have been the result of deliberate nature restoration alone but also of land abandonment or afforestation for production purposes, which do not necessarily lead to positive development in terms of biodiversity. For the period 1990–2006, overall quality of governance was found to be positively related to expansion of nature, and negatively to increasing patch size of nature. Generally, lower scores of overall quality of state-centric governance are more likely to drive the processes of removal, shrinkage, and dissection of nature through changes in nature area. Higher scores of overall quality of state-centric governance are more likely to drive the processes of formation, expansion, and connection of nature through changes in both nature area and patch size. Overall, it appears that quality of state-centric governance indeed drives the deliberate development of nature for the purposes of restoration and conservation, halting fragmentation and the ongoing decline of biodiversity in Europe.

On the one hand, the combined results of chapters 2–3 may imply that increased inclination toward expansion of agriculture could be commensurate with increased removal, shrinkage, and dissection of nature (i.e., negative change in nature area). On the other hand, the combined results of chapters 2–3 may imply that increased inclination toward intensification of agriculture could be commensurate with increased formation, expansion, and connection of nature (i.e., positive change in nature area). Overall, this would be consistent with the fact that lower scores of quality of state-centric governance are more likely to drive the practicing of cheaper forms of arable agriculture, requiring less financial investment to keep up with growing demands for food. In particular, expansion at the expense of nature, which is common in developing countries where nature is often abundant yet poorly protected (chapter 2).

In the second part of this thesis (chapters 4–5), a positivistic process-based approach was applied to include governance into land-use modeling. To investigate to what extent found the semi-positivistic empirical-statistical relationships could be simulated, a spatially explicit pattern-oriented individual-based land-use-transition model was constructed (chapter 4). Given that conceptualizations of decision-making and other mechanisms controlling behavioral and environmental constraints approach those of a real-world study area sufficiently close, and that land-use change data of this study area permit identification of the degree and composition of systematic influence on aggregate land-use patterns, meaningful comparison of empirical and simulated spatial statistics is possible. Furthermore, it is possible to approximate real-world land-use patterns with simulated ones, by minimizing differences between real-world- and simulated spatial statistics. These differences could be minimized by applying Pattern-Oriented Modeling (POM), iteratively comparing real-world- and simulated land-use patterns, and making systematic adjustments to explore which mechanisms and settings deliver optimal results. It was concluded that the empirical-statistical result that occurrence of agricultural intensification is likely to be more commensurate with higher quality of governance (chapter 2), can be reproduced as an emergent property of aggregated individual behavior of farmers constrained by state-centric governance (by the constructed model).

To investigate under which conditions nature could be protected from agriculture in an optimal way, individual farmers were subjected to different state-centric governance settings in the constructed model (chapter 5). One state-centric governance setting was assumed to be determined by the quality of the investment climate, reflected by the quality of the state-centric governance dimension “Regulatory quality”. Another was assumed to be determined by the level of entrepreneurial awareness, reflected by the quality of the state-centric governance dimension “Government effectiveness”. Together, these assumptions could be combined into four state-centric governance settings: “Low Entrepreneurial Awareness and Low Quality of Investment Climate” (I); “Low Entrepreneurial Awareness and High Quality of Investment Climate” (II); “High Entrepreneurial Awareness and Low Quality of Investment Climate” (III); and “High Entrepreneurial Awareness and High Quality of Investment Climate” (IV). Furthermore, farmers were subjected to two different top-down policy instruments in each state-centric governance setting: subsidies and fines. The most effective- and second-most effective protection of nature was generated by applying fines in state-centric governance settings III and IV, respectively. It was concluded that the empirical-statistical result that better protection of nature is likely to be commensurate with higher quality of governance (chapter 3), can be reproduced as aggregate emergent properties of individual behavior of farmers in different policy scenarios (by the constructed model) (chapter 4). Furthermore, that abstract process-based simulation (pattern-oriented modeling) of spatially explicit agricultural land-use systems allows for identification of different and verifiable governance conditions and policy strategies regarding protection of nature, and for identification of the optimal verifiable governance conditions and policy strategy for protection of nature and the economic interests of farmers in agricultural land-use systems.

It was concluded that governance can be meaningfully included into land-use modeling in both semi-positivistic (i.e., empirical-statistical) and positivistic (i.e., process-based) ways. However, different combinations of empirical specificity and degree of abstraction, i.e., different models, describe the same real-world complexity differently. Therefore, a conceptual representation of land-use models characterized by empirical specificity and degree of abstraction was proposed (chapter 6). According to this representation, there are three main classes of land-use models. There are those models that are more empirically specific than abstract ($\alpha < \varepsilon$), indicating increasingly empirical-statistical models. Furthermore, there are those models that are more abstract than empirically specific ($\alpha > \varepsilon$), indicating models that are increasingly process-based. It was observed that if a model of a real-world land-use system could optimize the empirical specificity with which this model can be validated and the degree of generality to which this system can be understood, then its predictive power might be maximized. That is, the class of models for which empirical specificity is equal to the degree of abstraction ($\alpha = \varepsilon$) might represent a class of models for which predictive power is potentially maximal. However, the research in this thesis suggests there is still a considerable gap between the used empirical-statistical models ($\alpha < \varepsilon$) and the constructed pattern-oriented model ($\alpha > \varepsilon$). Therefore, it is recommended that research efforts be devoted to the development of models that further reduce the gap between empirical specificity and degree of abstraction, that is $(\alpha - \varepsilon) \rightarrow 0$. Moreover, to apply and validate such models successfully, large amounts of data would be required that are currently unavailable. This is why even more research efforts should be devoted to the development of high-resolution monitoring systems of land use, to allow for larger and better databases.

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Samenvatting

Samenvatting

Een verbeterd begrip van complexe sociaal-politieke- en economische governance-processen kan wellicht helpen om negatieve effecten van de toenemende drukken van agrarisch landgebruik en de groeiende globale vraag naar voedsel te verminderen. Hierom zijn in deze dissertatie relaties tussen governance, landbouw en natuur gekwantificeerd, en is het onderzocht tot op welke hoogte governance zinvol geïncludeerd kan worden in het modelleren van landgebruik. Zoals aangegeven in de algehele introductie van deze dissertatie, zijn hierbij twee aanpakken onderscheiden: een semi-positivistische empirisch-statistische aanpak en een positivistische proces-gebaseerde aanpak. Daarom bestaat deze dissertatie uit twee delen: een deel dat governance includeert door middel van empirisch-statistisch modelleren, en een deel dat governance includeert door middel van proces-gebaseerd modelleren.

In het eerste deel van deze dissertatie (hoofdstukken 2–3), zijn relaties geïdentificeerd tussen de akkerbouw, natuur en gekwantificeerde percepties van staat-gecentreerde governance, door middel van semi-positivistische empirisch-statistische methodes. Om te onderzoeken of–en als dit zo is, hoe– staat-gecentreerde governance direct expansie en/of intensivering van akkerbouw drijft op globaal niveau (hoofdstuk 2), zijn empirisch-statistische relaties geïdentificeerd tussen landbouwproductie dynamieken en staat-gecentreerde governance indicators voor 173 landen voor de periode 1975–2007. Hierbij zijn vier groepen van landen onderscheiden: landen met zowel areaal- als opbrengst-toename (“groei” landen); landen met areaal-afname maar opbrengst-toename (“intensiverende” landen); landen met areaal-toename maar opbrengst-afname (“expansie” landen); en landen met zowel areaal- als opbrengst-afname (“afname” landen). Verschillen tussen deze vier groepen zijn geanalyseerd, zowel als governance–productie relaties binnen deze groepen. De analyse van governance-productie relaties binnen deze groepen suggereert dat landen met een lagere kwaliteit van governance meer geïnclineerd zijn om productietoename te realiseren met expansie van areaal, vergeleken met intensivering. Bovendien, als de kwaliteit van governance hoger wordt, dan heeft deze oriëntatie van landen met betrekking tot productie de neiging om te slaan van expansie naar intensivering. In het algemeen is het waarschijnlijker dat hogere kwaliteit van staat-gecentreerde governance intensivering van akkerbouw drijft, en dat lagere kwaliteit van staat-gecentreerde governance het praktiseren van goedkopere vormen van akkerbouw drijft, die dus minder financiële investering vereisen om de groeiende vraag naar voedsel bij te kunnen houden.

Om te onderzoeken of–en als dit zo is, hoe–staat-gecentreerde governance direct dominante spatio-temporele processen van fragmentatie en expansie van natuur drijft, zijn empirisch-statistische relaties geïdentificeerd tussen algehele kwaliteit van staat-gecentreerde governance en dergelijke processen, door middel van transnationale vergelijking voor 20 Europese landen voor de periode 1990–2006 (hoofdstuk 3). Dominante spatio-temporele processen van verandering in de natuur zijn gekarakteriseerd door ontwikkelingen uit het verleden te vangen in twee indicators: algehele verandering in natuuroppervlak en verandering in gemiddelde natuurpatch-grootte. Dit heeft geresulteerd in vier onderscheidbare dominante spatio-temporele processen van structurele verandering: “Formatie van groter-dan-gemiddelde natuurpatches en/of Expansie van natuur en/of Connectie van natuur”; “Formatie van kleiner-dan-gemiddelde natuurpatches”; “Verwijdering van kleiner-dan-gemiddelde natuurpatches”; en “Verwijdering van groter-dan-gemiddelde natuurpatches en/of Contractie van natuur en/of Doorsnijding van natuur”. Het merendeel van de bestudeerde landen heeft het algehele natuuroppervlak vergroot, hoewel het waarschijnlijk is dat dit niet alleen maar het resultaat is geweest van opzettelijke natuur restoratie. Maar ook van bijvoorbeeld processen zoals landverlating of aanplanting van bos voor productiedoeleinden, welke niet noodzakelijk een positief effect hebben op biodiversiteit. Voor de periode 1990–2006 is de algehele kwaliteit van governance positief gerelateerd aan expansie van natuur bevonden, en negatief aan toenemende natuurpatch-grootte. In het algemeen is het waarschijnlijker dat lagere scores van algehele kwaliteit van staat-gecentreerde governance de processen van verwijdering, contractie en doorsnijding van natuur drijven, door middel van veranderingen in het algehele natuuroppervlak. En dat hogere scores van algehele kwaliteit van staat-gecentreerde governance de processen van formatie, expansie en connectie van natuur drijven, door middel van veranderingen in zowel het algeheel natuuroppervlak als de gemiddelde natuurpatch-grootte. Over het geheel genomen, suggereren de resultaten dat de kwaliteit van staat-gecentreerde governance inderdaad de opzettelijke ontwikkeling van natuur (met als doel de restoratie en conservatie daarvan) drijft, een halt toeroepende aan fragmentatie en de doorzettende trend van afname van biodiversiteit in Europa.

Aan de ene kant zouden de gecombineerde resultaten van hoofdstukken 2–3 kunnen impliceren dat een toegenomen inclinatie richting expansie van de landbouw gelijk op zou kunnen gaan met een toegenomen verwijdering, contractie en doorsnijding van natuur (i.e., negatieve verandering in algehele natuuroppervlak). Aan de andere kant zouden de gecombineerde resultaten van hoofdstukken 2–3 ook kunnen impliceren dat een toegenomen inclinatie richting intensivering van de landbouw gelijk op zou kunnen gaan

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met toegenomen formatie, expansie en connectie van natuur (i.e., positieve verandering in algehele natuuroppervlak). Over het geheel genomen, zou dit consistent zijn met het feit dat het waarschijnlijker is dat lagere scores van staat-gecentreerde governance het praktiseren van goedkopere vormen van akkerbouw drijven (in plaats van het intensiveren hiervan). En in het bijzonder expansie ten koste van de natuur, wat veelvuldig voorkomt in ontwikkelingslanden waar natuur overvloedig aanwezig is, maar slecht beschermd door de lage kwaliteit van staat-gecentreerde governance (hoofdstuk 2).

In het tweede deel van deze dissertatie (hoofdstukken 4–5), is er een positivistische proces-gebaseerde aanpak toegepast om governance te includeren in landgebruiksmodellering. Om te onderzoeken tot op welke hoogte de gevonden semi-positivistische empirisch-statistische resultaten gesimuleerd konden worden, is er een ruimtelijk expliciet, patroon-georiënteerd en individu-gebaseerd landgebruikstransitiemodel geconstrueerd (hoofdstuk 4). Als gegeven is dat conceptualisaties van beslissingsmaking en andere mechanismen die de randvoorwaarden van gedrag en omgeving bepalen, diegene van een fysiek studiegebied dicht genoeg benaderen, en dat landgebruiksverandering data van dit studiegebied het toestaan om de gradatie en compositie van systematische invloeden op het geaggregeerde landgebruikspatroon te detecteren, dan is zinvolle vergelijking van empirische en gesimuleerde ruimtelijke patroonstatistieken mogelijk. Verder is het dan mogelijk om empirische landgebruikspatronen te benaderen met gesimuleerde patronen, door middel van het minimaliseren van de verschillen tussen empirische en gesimuleerde ruimtelijke patroonstatistieken. Zulke verschillen zouden geminimaliseerd kunnen worden door het toepassen van patroon-georiënteerd modelleren (POM): het op iteratieve wijze vergelijken van empirische en gesimuleerde landgebruikspatronen, waarbij telkens systematische aanpassingen worden gemaakt aan modelinstellingen om te verkennen welke mechanismen en sterktes ervan optimale resultaten opleveren (i.e., simulaties die de werkelijkheid zo dicht mogelijk benaderen). Het kon worden geconcludeerd dat het empirisch-statistische resultaat wat zegt dat intensivering waarschijnlijk gekoppeld is aan hogere kwaliteit van governance (hoofdstuk 2), gereproduceerd kan worden als een emergente eigenschap van geaggregeerd individueel gedrag van boeren die gelimiteerd worden door staat-gecentreerde governance (door middel van het geconstrueerde model).

Om te onderzoeken onder welke omstandigheden natuur op een optimale manier tegen landbouw beschermd zou kunnen worden, zijn individuele boeren blootgesteld aan verschillende staat-gecentreerde governance instellingen in het geconstrueerde model (hoofdstuk 5). Van een van de staat-gecentreerde governance instellingen werd aangenomen dat deze werd bepaald door de kwaliteit van het investeringsklimaat, gereflecteerd door de kwaliteit van staat-gecentreerde governance dimensie “Kwaliteit van Regelgeving”. Van een andere werd aangenomen dat hij werd bepaald door het niveau van bewustzijn waarmee boeren ondernemen, gereflecteerd door de kwaliteit van staat-gecentreerde governance dimensie “Overheidseffectiviteit”. Samen konden deze aannames worden gecombineerd tot vier staat-gecentreerde governance instellingen: “Laag Ondernemend Bewustzijn en Lage Kwaliteit van Investeringsklimaat” (I); “Laag Ondernemend Bewustzijn en Hoge Kwaliteit van Investeringsklimaat” (II); “Hoog Ondernemend Bewustzijn en Lage Kwaliteit van Investeringsklimaat” (III); en “Hoog Ondernemend Bewustzijn en Hoge Kwaliteit van Investeringsklimaat” (IV). Verder zijn boeren blootgesteld aan twee verschillende top-down beleidsinstrumenten in elke staat-gecentreerde governance instelling: subsidies en boetes. De meest effectieve en de op één na meest effectieve bescherming van natuur werd gegenereerd door het hanteren van boetes in staat-gecentreerde governance instellingen III en IV, respectievelijk. Het kon worden geconcludeerd dat het empirisch-statistische resultaat wat zegt dat betere natuurbescherming waarschijnlijk gelijk op gaat met hogere kwaliteit van governance, gereproduceerd kan worden als geaggregeerde emergente eigenschappen van individueel gedrag in verschillende beleidsscenario’s (door het geconstrueerde model) (hoofdstuk 4). Verder kon het worden geconcludeerd dat abstract proces-gebaseerd simuleren (patroon-georiënteerd modelleren) het identificeren van verschillende verifieerbare governance instellingen en beleidsstrategieën betreffende natuurbescherming toelaat. Deze wijze van simuleren laat ook het identificeren van de optimale verifieerbare governance instellingen en beleidsstrategie toe, i.e., die instellingen en strategie die zowel resulteren in effectieve natuur bescherming en in de bescherming van de economische belangen van boeren in agrarische landgebruikssystemen.

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Het kon geconcludeerd worden dat governance zinvol kan worden geïncludeerd in landgebruiksmodellering, op zowel semi-positivistische (i.e., empirisch-statistische) en positivistische (i.e., proces-gebaseerde) wijze. Hoewel, verschillende modellen met andere combinaties van empirische specificiteit en abstractieniveau beschrijven dezelfde wereldlijke complexiteit op andere wijze. Daarom werd in hoofdstuk 6 een conceptuele representatie voorgesteld die landgebruiksmodellen karakteriseerde met empirische specificiteit en abstractieniveau. Volgens deze representatie bestaan er drie hoofdklassen van landgebruiksmodellen. Er zijn die modellen die meer empirisch specifiek zijn dan abstract ($\alpha < \varepsilon$), de klasse van steeds meer statistisch-empirische modellen. Verder zijn er die modellen die meer abstract zijn dan empirisch specifiek ($\alpha > \varepsilon$), de klasse van steeds meer proces-gebaseerde modellen. Het werd geobserveerd dat als een model van een wereldlijk landgebruikssysteem de empirische specificiteit waarmee dit model zou kunnen worden gevalideerd en de algemeenheid (abstractie) waarmee dit systeem kan worden begrepen zou kunnen optimaliseren, dat dan de voorspellingskracht van dit model wellicht gemaximaliseerd is. Dat wil zeggen, de klasse van modellen waarvoor de empirische specificiteit gelijk is aan het abstractieniveau ($\alpha = \varepsilon$), zou wellicht een klasse van modellen kunnen representeren waarvoor de voorspellingskracht potentieel maximaal is. Hoewel, het onderzoek in deze dissertatie suggereert dat er nog steeds een aanzienlijke kloof aanwezig is tussen de gebruikte empirisch-statistische modellen ($\alpha < \varepsilon$) en het geconstrueerde patroon-georiënteerde model ($\alpha > \varepsilon$). Daarom wordt het aanbevolen dat onderzoeksinspanningen gewijd moeten worden aan de ontwikkeling van modellen die deze kloof tussen empirische specificiteit en abstractieniveau verder reduceren, i.e., $(\alpha - \varepsilon) \rightarrow 0$. Bovendien, om zulke modellen succesvol toe te passen en te valideren, zouden er grote hoeveelheden data benodigd zijn die nu nog niet beschikbaar zijn. Daarom moeten er nog meer onderzoeksinspanningen gewijd worden aan de ontwikkeling van monitoringssystemen van landgebruik met hoge resolutie, om grotere en betere databases te kunnen realiseren.

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Acknowledgements

Acknowledgements

The last six years of my life have not only been a journey of the intellect, but foremost a deep journey of personal growth and self-exploration. The journey was a difficult one. I have been put to the test, and I have been on the edge of the abyss. However, I believe this is precisely where we need to be to find the strength we need, and to grow. Without sacrifice, there can be no progress. I believe we learn equally through each interpersonal interaction, whether the interaction is experienced as positive or negative, whether we want to or not. We learn from the contrasts we encounter in our experiences. I acknowledge and thank all those with whom I have had the honor of interacting.

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About the author

About the author

The cover of this book was made from a photograph, called “Starry light”, made by the author in New York City, at the highest point available on the Empire State Building. It shows stars photographed during the day, and it resulted from a photography project during a stay in New York in 2010. The short poems encountered throughout this thesis are part of a poetry bundle in progress, called “Cornerstones”. These poems express some of the emotions experienced by the author during the various phases of the PhD period, and are *in no way religious*. Images (whether sculptures, photographs, or conceptual) and creative writing belong to the fields of interests of the author, who was also taught at the Gerrit Rietveld Academy (GRA) (during a BSc of Fine Arts). The author also undertook studies in physics (BSc) and mathematics at the Vrije Universiteit in Amsterdam (VUA), to which he was drawn because they seemed to provide absolute truth. Although studying with ease, passing with high marks, and being enrolled in a prestigious mathematical physics program (MSc) at the University of Amsterdam, the author felt increasingly uncomfortable with the elegant yet cold and unemotional exact sciences. There was more to him than he knew himself, as he felt more and more drawn to the arts. He started drawing again, and writing, and was admitted to the academy based on the materials he had produced for the exam.

Around the same time, the author enrolled in a program of environment and resource management (MSc) at the VU in Amsterdam, as the author feels a strong need to be useful in a societal way, and feels strongly connected to nature. After which the author started his PhD in Wageningen: the start of a long period of thinking, during which he learned much, although the emotional part of the author’s identity sometimes suffered. The author hopes to have more time to spend on artistic projects in the future. The author is as much a “thinking” person as a “feeling” person, oscillating back and forth between these different aspects of his identity. To him, art and science are different sides of the same coin. Artistic qualities may facilitate scientific research, when the intellectual aspect of the identity is present more strongly. Conversely, scientific qualities may facilitate artistic expression, when the artistic aspect of the identity is present more strongly. The author’s artistic interests reflect the “feeling” part of his personality, while the scientific interests reflect the “thinking” part. The author feels it is his life’s challenge to make these two parts coexist in harmony, so that sufficient self-love may flow through this union. When one part is overly dominant, the other is subdued, which is still sometimes experienced as difficult by the author. This can also lead to being cut-off from the flow of self-love that we all need so much.

Long before any of this, the author was born on the 11th of May, 1979, in the small city of Schagen in the province of North-Holland, the Netherlands.

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List of publications

List of Publications

Mandemaker. M, Bakker, M., Jongman, R., and Veldkamp, A. *In review*. Quantifying effects of governance on nature dynamics in Europe: A cross-national comparison for 1990–2006. Land Use Policy.

Mandemaker M., Bakker, M., and Stoorvogel, J. (2011). The Role of Governance in Agricultural Expansion and Intensification: a Global Study of Arable Agriculture. Ecology and Society 16(2):8. [URL] http://www.ecologyandsociety.org/vol16/iss2/art8/

Mandemaker, M., Bakker, M. Stoorvogel, J., and Veldkamp, A. (2014). A pattern-oriented individual-based land-use-transition model: utility maximization at varying levels of complexity and rationality (CORA). Journal of Land Use Science 9(1):59-81. [URL] http://www.tandfonline.com/doi/full/10.1080/1747423X.2012.751560#.VEfYxlfIQjZ

Mandemaker, M., Bakker, M., and Veldkamp, A. (2013). Revealing sprawl- and structural connectivity in Europe: A cross-national comparison for 1990–2006. UGEC Viewpoints 9:38-42, "Paving the Way Forward in Urbanization and Global Environmental Change Research (Emerging Scholars Edition)". [URL] https://ugec.org/docs/ugec/viewpoints/Viewpoints9-July2013.pdf

Mandemaker, M., Bakker, M., and Veldkamp, A. *Submitted.* Pattern-oriented individual-based modeling of spatially explicit agricultural landscapes: A scenario analysis of effects of state-centric governance and top-down policy instruments on protection of nature. Agricultural Systems.

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Education Certificate

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC), which comprises a minimum total of 32 ECTS (= 22 weeks of activities).

Review of literature (4.5 ECTS)

- Ways of including governance into land-use modelling (2014)

Writing of project proposal (4.5 ECTS)

- Examining temporal and spatial dynamics of agricultural production from a multi-level perspective, under varying biophysical and socio-economic conditions (2008)

Post-graduate courses (5 ECTS)

- Multivariate analysis; PE&RC (2008)
- SEAMLESS; PE&RC (2008)
- Scaling & Governance; S & G (2009)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Landscape Ecology: cropland change in southern Romania: a comparison of logistic regressions and artificial neural networks (2009)
- Journal of Agricultural Science: approach for assessing potential crop yield breakthroughs (2010)

Competence strengthening / skills courses (1.5 ECTS)

- Career Orientation (CO); WGS (2012)

PE&RC Annual meetings, seminars and the PE&RC weekend (2.7 ECTS)

- PE&RC Introduction weekend (2008)
- PE&RC Day (2008-2012)
- PE&RC Last year weekend (2012)

Discussion groups / local seminars / other scientific meetings (5.7 ECTS)

- Spatial Methods discussion group (2008-2011)
- Regular scientific meetings of the Scaling & Governance project (2008-2012)
- Scaling & Governance discussion group; co-organizer (2010)

International symposia, workshops and conferences (6.3 ECTS)

- GLP Conference; oral presentation; ASU, USA (2010)
- Scaling & Governance Conference; oral presentation; WUR, NL (2010)
- Annual AAG conference; oral presentation; LA, USA (2013)