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MODELING THE CO-EVOLUTION OF NATURAL, ECONOMIC AND GOVERNANCE SUBSYSTEMS IN INTEGRATED AGRI-ECOLOGICAL SYSTEMS: PERSPECTIVES AND CHALLENGES

Viewpoint article

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Modeling the Co-Evolution of Natural, Economic and Governance Subsystems in Integrated Agri-Ecological Systems: Perspectives and Challenges

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ABSTRACT

Current agri-ecological systems face the twin challenge of providing sufficient food for a growing global population and of mitigating severe negative environmental impacts from agricultural land-use in terms of biodiversity loss, greenhouse gas emissions, nutrient run-off, soil degradation, and water pollution. Disciplinary research provides detailed answers to specific questions related to the challenges faced by agri-ecological systems. However, it fails to consider the complex interrelationships and dynamics of the different economic, natural and governance subsystems of which agri-ecological systems consist and that need to be considered to address these challenges. In principle, it is possible to develop models that integrate knowledge from the fields of ecology, economics and governance, and consider dynamic system features such as feedbacks between subsystems as well as tipping points. In this viewpoint article, we scrutinize selected integrated agri-ecological system models and find that only very few models address the challenges mentioned above. We suggest further research in three areas: (I) in-depth integration of the governance subsystem in integrated models, (II) more comprehensive inclusion of tipping points in integrated models, and (III) integration of cascading effects where one system change stimulates another system change. Finally, we briefly discuss the challenges of complex integrated modeling in relation to computational power and the necessity to gather expertise from different disciplines.

Keywords: agri-ecological systems; integrated modeling; socio-ecological systems

HIGHLIGHTS

- Agri-ecological systems are highly complex
- Their analysis requires integration of diverse disciplines
- Models are crucial for this purpose
- Future research may include tipping points, cascading effects, governance subsystem

1. INTRODUCTION

Current agri-ecological systems face the challenge of providing food security for an estimated 9 billion people worldwide by the middle of the century (Godfray et al. 2010). At the same time, they generate severe negative environmental impacts such as biodiversity loss (Tscharntke et al. 2012), greenhouse gas emissions (Godfray et al. 2010; Lal 2004; West & Marland 2002), nutrient run-off (Korsaeth & Eltun 2000), soil degradation (Godfray et al. 2010; Lal 2004), and water shortages and pollution (Godfray et al. 2010) which need to be mitigated. Disciplinary research provides detailed answers to specific questions related to the challenges faced by agri-ecological systems. However, it fails to consider the complex interrelationships and dynamics of the different economic, natural and governance subsystems that interact. These interactions need to be considered jointly to provide comprehensive solutions to the enormous food production and environmental challenges that confront agri-ecological systems (Doyen et al. 2013; Pulver et al. 2018; van Riper et al. 2018).

Whereas natural scientists are becoming increasingly familiar with economic knowledge (Cooke et al. 2009), there is often little understanding about the realm of governance. We understand the governance subsystem here to include the full range of regulatory processes, social mechanisms and organizations through which political actors influence agri-ecological actions and outcomes. Although the action of state actors plays a considerable role, according to Lemos and Agrawal (2006), non-state actors' power and mechanisms to regulate, manage and steer collective action have to be considered too. Governance therefore includes all coordination mechanisms that guide the behavior of individuals, groups and organizations in formal (e.g. through ordinances and regulations) and informal ways (e.g. through social and cultural norms). Coordination may be organized by hierarchical-driven modes of governance constraining, supporting or supervising actors or sanctioning actors' non-compliance but also by information and knowledge sharing mechanisms, monitoring mechanisms, conflict resolution mechanisms and self-governance networks. Often, market relations are also considered to be part of governance (Lemos & Agrawal 2006). However, given the explicit distinction made here between the economic and governance subsystem we consider that they, together with the agri-ecological production system, make up the economic subsystem.

To address the complexity of agri-ecological systems, knowledge from different disciplines needs to be integrated (Mauser et al. 2013), and models may be useful for this (Wätzold et al. 2006; Filatova et al. 2016; Polhill et al. 2016*a*). Statistical, system dynamics, equilibrium and agent-based models are already commonly used to model complex socio-environmental systems (Filatova et al. 2016), and they are also useful for modeling agri-ecological systems.

Yet, there are two important aspects that add further complexity to the study of agri-ecological systems and impede their proper understanding if not considered. First, the various natural, economic and governance subsystems are intricately linked via feedback loops. Feedback loops describe situations in which a change in a subsystem causes a change in a different subsystem. However, this change triggers a reaction back in the original subsystem, and thus a feedback-loop emerges (Wätzold et al. 2006). For example, unsustainable cropping practices (economic subsystem) can lead to soil compaction (natural subsystem), which in turn reduces the options for productive use (economic subsystem) in the future.

Second, marginal alterations in the subsystems frequently drive the system towards a tipping point, after which the system changes rapidly (Crépin et al. 2012; Vandermeer & Perfecto

2012). A tipping point happens when a system exhibits threshold behavior where at some point incremental changes cause a change in the state of the system (Crépin et al. 2012) with limited reversibility (Brook et al. 2013). Typically, tipping points refer to changes in natural systems, but social systems, in particular their governance subsystems, can also reach tipping points (Theesfeld & MacKinnon 2014) – passing a threshold that leads to a new governance structure to manage a natural resource. For example, public concern over the environmental impact of a pesticide can reach such a high level of political relevance that the pesticide is banned. This policy can hardly be reversed, even if it turns out that the pesticide is less harmful than previously thought. Reasons for this de facto irreversibility may be path dependence and bureaucratic inertia (Dobusch & Kapeller 2013). Sometimes tipping points also interact (Filatova et al. 2016) as cascading effects, where one threshold triggers the crossing of other thresholds (Kinzig et al. 2006).

An example of where interacting feedback loops and tipping points may occur in agri-ecological systems is the high release of nitrogen compounds into the environment due to the intensive application of nitrogen fertilizer, manure and – more recently – the fermentation residues from biomass production (Weiland 2010). Tipping points occur: (I) from a governance perspective, if water can no longer be used as drinking water due to the violation of maximum permissible values of nitrate (Kastens & Newig 2007), and (II) from an ecological perspective if agri-ecological systems lose their suitability as a habitat for specific species and provider of ecosystem services due to eutrophication in areas that are particularly vulnerable to nitrogen inputs (Glibert et al. 2014). A policy reaction to increasing nitrogen fertilization might be to implement a regulation to curb nitrogen emissions accompanied by comprehensive documentation duties with resulting cost increases for farms. This in turn may feed back to the farming system with partly intended, partly unintended consequences. An intended consequence would be that farms which manage their land intensively have to curb emissions. An unintended consequence would be cost increases for all farms due to the new documentation duties, including farms with low profitability on extensively managed marginal land. This added difficulty may be enough to cause some of these farms to close down resulting in an abandonment of marginal farm land. This negative feedback loop has an unwanted effect, as extensively managed farmland is often highly valuable for biodiversity (Isselstein et al. 2005).

In order to comprehensively understand the dynamics of agri-ecological systems and develop appropriate policy recommendations, it is therefore necessary to develop models that combine natural, economic and governance analyses (henceforth referred to as integrated models) and to consider tipping points and feedback loops between the governance, economic and natural subsystems. Reviews on modeling socio-ecological systems (Schlüter et al. 2011; An 2012, Polhill et al. 2017; Schulze et al. 2017) and tipping points (Filatova et al. 2016) exist. However, this work is not specific to agri-ecological systems and does not consider integrated modeling jointly with tipping points and feedback loops.

The purpose of this paper is to scrutinize selected research in agri-ecological system modeling focusing on the three fields of (1) integration of different disciplines in agri-ecological models, (2) consideration of feedback loops, and (3) consideration of tipping points. Given the framework of a viewpoint article and the broadness of the three research fields, we refrained from carrying out a systematic literature review. We have rather drawn on the expertise of the authors who cover relevant disciplines for these three fields, including environmental economics, political science, ecology, agronomy, and integrated modelling.

Each author brought in his or her individual experience but has also done a careful literature screening in their respective field. This literature screening was conducted using different methods, including electronic searches with keywords relevant to each field on Google Scholar and the Web of Knowledge, snowballing, and e-mail alerts on new research published in relevant journals. A broad range of model types has been considered because of the different definitions of what constitutes a "model" in the different disciplines (cf. Drechsler et al. 2007).

We identified areas for which we suggest that more research is fruitful and provide recommendations for further work to successfully address the co-evolution of natural economic and governance subsystems in complex agri-ecological systems. Finally, we address two key challenges for such a critical endeavor: model complexity and the necessity to integrate expertise from different disciplines.

2. INTEGRATED MODELING IN AGRI-ECOLOGICAL SYSTEMS

Regarding models that integrate knowledge from economics and natural sciences, there is a growing body of literature that has been developed over the past twenty years or so (cf. Vatn et al. 1999 for an early example). Many of these ecological-economic or hydrological-economic models gather economic and natural scientific information or data on small spatial units. This information is then combined in a spatially explicit manner to simulate policies and other drivers or to optimize agri-environment measures and policy instruments. Following this general approach, Wätzold and Drechsler (2014) developed modeling procedures to spatially optimize agri-environment schemes, and Wätzold et al. (2016) to spatio-temporally optimize them. Spatial optimization of agri-environment measures is also an important research topic in the field of water pollution by nutrients (Konrad et al. 2014). An example of research applying models integrating economics and natural sciences in other areas is Esteve et al. (2015), who integrated spatially explicit economic, hydrological and climate information to evaluate climate adaptation measures in agriculture.

In contrast to models that integrate economic and natural sciences subsystems, much fewer models exist that explicitly integrate the governance subsystem. However, a few models try to analyze the impacts of the governance subsystem on the natural subsystem or the agricultural production unit (Archer et al. 2008; Hendrickson et al. 2008; Daloğlu 2014; Hauck et al. 2019). Others make isolated governance aspects measurable and operational. Examples include an aggregated farmers' mental model (Jabbour et al. 2014), and the measurement of power aspects in agricultural water distribution (Theesfeld 2011). While making these factors measurable is an important step towards including them in models, the above-mentioned studies do not develop models.

The few agri-ecological models that explicitly include the governance subsystem typically consider economic and, less frequently, natural subsystems. Happe et al. (2006) used a meta-modeling approach, based on agent-based modeling, to analyze impacts of reform of the EU's Common Agricultural Policy on farmers' production decisions and agricultural structural change. Schouten et al. (2013) applied an agent-based model to analyze farmers' decision-making regarding conventional milk production and the implementation of agri-environment measures that benefit biodiversity. The governance aspect examines a flexible compensation payment for an agri-environment measure based on the location of a land parcel. Depending on location, the ecological benefit may be higher or lower. Finally, the economic subsystem is included when examining the impact of price volatility. Dace et al. (2015) developed and applied a system dynamics model to assess the impact that policy measures have on greenhouse gas emissions from agri-ecological systems, thereby integrating the governance, ecological and economic subsystems.

Overall, we found that the large majority of agri-ecological models that integrate knowledge from different disciplines combine knowledge from the natural sciences with economic knowledge. Some of these models also address aspects relevant to the governance subsystem such as the simulation and optimization of agri-environment policies. However, these models implicitly adopt the perspective of a social planner assumed to be willing and able to optimize policies (Sugden 2013). While such research is relevant to understand the direct impact of policies it is obviously a simplistic view that does not consider the richness of the political actors, processes and mechanisms that make up the governance subsystem (Lemos and Agrawal 2006), and the resulting interactions with the economic and natural subsystems. Only few models exist that combine natural sciences and governance knowledge or knowledge from all three subsystems.

3. FEEDBACK LOOPS IN INTEGRATED MODELING

Some studies model feedback loops to connect different subsystems that are traditionally investigated by different disciplines. Elshafei et al. (2015, 2016) modeled feedback loops to connect natural and human subsystems in their models on agriculturally used catchment areas. They developed a model considering catchment hydrology, population, economic and environmental indicators, quality of life and collective responses. Dace et al. (2015) included different feedback loops to connect natural, economic and governance subsystems. Zavalloni et al. (2015) discussed the interaction between farmers and tourists, and their response to rural policies. One such policy rewards “green farming”, which in turn leads to increased tourism. This increase leads to additional income for farmers in areas of “green farming”. Depending on this benefit, a loop feeds back to the farmer’s decision-making for the next period, as depending on the economic benefit of increased tourism farmers decide whether or not to expand “green farming” in the next period.

Often feedback loops are used to integrate human decision-making in models integrating at least two disciplines. In a seminal paper, Berger (2001) developed an agent-based spatial model to analyze household-level decisions related to technology diffusion, resource use changes and policy in the field of water irrigation in agriculture. In the model, individuals try to maximize their expected income taking into account previous experiences and the feedback they receive. Le et al. (2012) also used an agent-based model to study land-use change. This model includes feedback loops between the human and environmental subsystems in the short and long term. In short-term feedback loops, individuals react according to their environment, while the long-term feedback loops describe cumulative, longer-term changes on a larger scale and include learning effects. Similarly, Tsai et al. (2015) used an agent-based model to examine land-use changes. Feedback loops are included as land users adapt their behavior depending on the outcome of the previous period.

Huber et al. (2013) also considered human decision-making by modeling the implementation of payments for environmental services based on feedback loops between vegetation dynamics, farm-based decision-making, and policy decisions on the national level. Henderson et al. (2016) developed a model to study the mosaic landscapes of forest, grassland and agricultural land in Brazil. Based on penalties, profits and conservation values, humans choose certain actions which influence the environment. This in turn influences the penalties, profits and conservation values that underlie human decision-making. Finally, Chapman and Darby (2016) developed a system dynamics model to assess rice cultivation strategies. This model includes physical, economic, and decision-making characteristics linked by loops connecting aspects such as fertilization, yield, nutrients, crop selection and technical capacity.

In summary, we found that feedback loops are mainly used for two purposes in integrated models of agri-ecological systems: to link subsystems that are traditionally studied by different scientific disciplines and to integrate human decision-making in the agri-ecological system models.

4. TIPPING POINTS IN INTEGRATED MODELING

One main area where tipping points are considered in agri-ecological system models relates to climate change and agricultural practices. Kenny et al. (2000) addressed the issue of climate thresholds in their paper on modeling the impacts of climate change on certain agricultural produce in New Zealand. However, the authors conclude that determining a critical threshold is not straightforward and requires more research. Nelson et al. (2014) combined climate and biophysical models with different economic models in order to investigate the role of economic models in interdisciplinary analyses of the uncertainty of the impact of ‘climate shocks’ on agriculture. They find that the inclusion of (different) economic models influences the scale of the considered climate change impact.

The other main area where tipping points are taken into account relates to pollution thresholds as tipping points in agri-ecological systems. Stoorvogel et al. (2004) developed a model of agri-ecological systems that can be used to calculate the probabilities of crossing pesticide thresholds as defined by the United States Environmental Protection Agency. The model represents land-use and input use decisions based on changing biophysical and economic conditions. Bennett et al. (2008) combined multiple models predicting the risk of exceeding pollutant (phosphorus) thresholds and find that this combination leads to much better prediction than the use of the single best model. Similarly, Wang and Burke (2017) developed a model that facilitates the understanding of local nitrate-legacy issues for policy makers. It specifically addresses long-term impacts to support water quality compliance, where passing the regional compliance level can be considered a tipping point.

Some research also focuses on other topics. Tzanopoulos et al. (2007) developed a grazing model, where crossing a threshold of grazing intensity leads to different vegetation structures. They analyze at which grazing intensity the threshold is crossed and predict the likely impact of policy reforms. Concerning prevailing governance structures, Theesfeld and McKinnon (2014) discussed governance tipping points in agricultural water management in Wyoming. The tipping point occurs where pending management reforms are held back until they allow the pent-up pressure of unmet climate adaptation needs to push the governance subsystem over a threshold. Nyborg et al. (2016) found that there are social behavior tipping points that turn a vicious cycle of a damaging behavior into a virtuous one. They developed a model to investigate whether policies, based on observability of the behavior, or informal institutions such as social norms are better suited to push society towards crossing a desirable tipping point.

Finally, only very few models integrate both tipping points and feedback loops. Lafuite and Loreau (2017) developed a model to determine thresholds for land conversion from biodiverse ecosystems to biodiversity-poor agricultural landscapes depending on human population size. These thresholds are linked via feedback loops in the economic, demographic, technological and ecological subsystems. Passing these thresholds leads to ecological crises. Fernald et al. (2012) modeled tipping points of sustainable and unsustainable water usage in traditional irrigation communities. Their analysis covers hydrological, ecosystem, land-use, economic, and sociocultural subsystems which are linked via feedback loops. Hossain et al. (2017) developed a system dynamics model to analyze the safe operating space on a regional scale beyond which human wellbeing in the case study area decreases dramatically, considering for example income and predicted deaths from natural disasters. The model includes complex factors such as non-linearity, feedbacks and interactions. In this model, they include the impacts of natural subsystems (i.e. predicted changes in the climate and water subsystems) and economic subsystems (including changes in subsidies, as well as indicators such as income and gross domestic product).

Although it has been recognized that tipping points are important when modeling agri-ecological systems (Vandermeer & Perfecto 2012), we found that only few models consider them and those that do mainly focus on two topics: interactions between climate change and agricultural practices and pollution thresholds in agri-ecological systems. Finally, there are only very few models that jointly consider tipping points and feedback loops. An analysis where tipping points interact as cascading effects has not been carried out in any of the integrated models investigated by the authors.

5. DISCUSSION: KEY CHALLENGES AND WAYS FORWARD

We have provided insights into the last two decades of research considering the co-evolution of the natural, economic and governance subsystems that make up complex agri-ecological systems. We focused on integrated modeling, the modeling of feedback loops and of tipping points. Based on our scrutiny of the literature, we think that three areas would particularly benefit from further research.

(I) Given our finding that integrated models that include the governance subsystem are rare, together with the fact that governance has a key impact on agri-ecological systems (von Braun & Birner 2016), we see particular benefits in developing models that consider the interactions of the governance subsystem with the economic and natural subsystems. For this purpose, knowledge from a broad range of disciplines including sociology, psychology and political science with relevance for the governance subsystem may be integrated into the models. This knowledge may allow analyzing aspects that have hitherto been neglected in integrated modeling such as the impact of cultural traditions or nudging on farmers' behavior and hence the natural subsystem. Generally, the integration of the governance subsystem in integrated models would enable new dynamic analyses, which could lead to better tailored policy recommendations. Such integrated models could, for example, provide quantitative assessments of the ecological impacts of changes in the governance structure that are conveyed through production changes in the economic subsystem and manifest themselves in the ecological subsystem. Quantitative assessments cannot be undertaken from a purely governance perspective as they require a detailed understanding of the economic and natural subsystem. However, quantitative analyses are highly relevant for formulating policies with adequate incentives that lead to sufficient food production and consider societal demands for environmentally sound production.

(II) We further found that the analysis of tipping points is limited to few research fields and, additionally, rarely considers the governance subsystem. However, tipping points are important phenomena in agri-ecological systems and their emergence can only be comprehensively understood and avoided if the governance subsystem is considered. Similarly, Filatova et al. (2016) conclude that tipping point models rarely integrate all aspects commonly considered important in empirical studies. Therefore, we think that developing integrated models to better understand the emergence of tipping points is a promising avenue of further research. In our opinion, and in line with Polhill et al. (2016*b*), tipping-point models should include the possible influence of gradual, internal dynamics and exogenous disturbances that may occur in the natural as well as the economic and governance subsystems. Related to that we see a further benefit if governance research also employs the concept of tipping points at a conceptual level, although we also acknowledge that models of policy change include ideas of tipping dynamics, for example, the punctuated equilibrium framework of policy change (Kuhlmann & van der Heijden 2018). Using the same terminology may facilitate interdisciplinary research in the field of agriculture, as other relevant disciplines (such as ecology) already apply the concept of tipping points. In turn, their research may stimulate further research in other disciplines as governance scientists may come up with novel ideas about the conceptualization and emergence of tipping points. However, one needs to be careful when different disciplines use the same terminology in order to avoid misunderstandings (Drechsler et al. 2007).

(III) We find that cascading effects, where the crossing of one system's threshold triggers the crossing of thresholds in other systems triggering a "domino effect", are rarely implemented in integrated models in agri-ecological systems research. However, only by considering cascading effects is it possible to understand the whole impact of a policy or other drivers. The consideration of only the direct tipping point resulting from a driver may address some problems, but vastly underestimate the driver's overall impact if cascading effects are not considered. Therefore, in our opinion, a further promising approach is to include cascading effects in integrated modeling of agri-ecological systems. Such research may help to detect at an early stage important environmental consequences of drivers that would not be discovered if research were to focus only on one tipping point and its direct consequences.

Complex models integrating natural, economic and governance subsystems and considering factors of complexity such as feedback loops, tipping points and cascading effects may greatly improve the relevance of models to understand the dynamics of agri-ecological systems and to develop policy-relevant recommendations to overcome the challenges they face. However, one has to consider trade-offs between an improved understanding of system complexity and the associated cost increases in terms of data collection (cf. Jones et al. 2017) and modelling efforts that come with higher model complexity. We wish to highlight two key challenges regarding modelling efforts.

1. Model complexity. Integrating natural, economic and governance subsystems in agri-ecological system models is likely to increase model complexity considerably, since not only each of the three system components must be modeled adequately but also the interactions between those components. In general, high model complexity hampers the systematic analysis of a model, as it becomes increasingly difficult to understand the behavior of the

model and the modeled system. However, the growth in computing power over recent decades and the development of better tools and approaches for model analysis now allow the development and analysis of models that some time ago would have been deemed too complex.

We highlight two examples where the growth in computational modeling power has made more complex modeling approaches possible: inverse modeling and sensitivity analysis. Inverse modeling allows us to estimate uncertain model parameters (whose number may appear prohibitively large in complex models) by comparing model outputs with observed system behavior. An intuitive variant of inverse modeling is pattern-oriented modeling (see Grimm et al. (2005) for general considerations and Magliocca & Ellis (2013) for a recent application), in which as many as possible macroscopic patterns like the spatial distribution of a species, a land-use pattern in response to some policy instrument, or the decision of a policy maker are generated by the model. Regarding socio-economic patterns, examples include the observable behavior of land users (Nelson et al. 2008). Since these patterns are likely to depend on the model parameters, different combinations of (uncertain) model parameter values will lead to different patterns. Model parameter combinations that generate patterns similar to the observed ones are likely to be the true ones valid in the real system. In a sensitivity analysis (Saltelli et al. 2009), the behavior of a model is explored in response to variations in the model parameters, which allows the development of understanding and system predictions even if model parameters are uncertain. Statistical methods like classification (e.g. Surun & Drechsler 2017) or regression trees (e.g. Guisan & Zimmermann 2000) further enhance the effectiveness of sensitivity analysis in the analysis of complex models.

2. A high degree of expertise in several disciplines and appropriate cooperation. If the different subsystems of governance, economics and ecology are to be integrated, a wide range of experts need to be involved in developing the models. Including what is perceived knowledge from other disciplines without relying on experts from that field should be avoided (Armsworth 2014). Otherwise, the opportunity to make full use of the richness of knowledge that exists in a specific discipline is likely to be missed (Wätzold et al. 2006). However, researchers from different disciplines have distinct educational backgrounds and are trained to analyse problems from different perspectives. For interdisciplinary work, researchers will have to become aware of and overcome problems caused by different, unconscious patterns of thought (Bauer 1990). For example, different questions regarding a common problem may be considered interesting by the distinct disciplines, the underlying assumptions of this problem may vary between the disciplines, and differences in epistemology may result in contrasting methods being acceptable (Lélé & Norgaard 2005). Against this background, it is problematic if researchers from one discipline develop interdisciplinary research projects, and other disciplines are added as “add-ons” because, for example, their participation is required by a call from a funding agency (Wätzold et al. 2006). This “add-on approach” may not capture all possible benefits that could be realized by developing projects jointly from the beginning. Moreover, different disciplines may use distinct concepts of terminology, scale and models (Drechsler et al. 2007). If these differences are not addressed from the beginning, frustration may lead to researchers avoiding interdisciplinary research (Wätzold et al. 2006).

Considering the subsystems of ecology, economics and governance, most integrated models are developed jointly by natural scientists, in particular ecologists, and by economists. Cooperation is facilitated because both disciplines have a strong tradition in mathematical modeling, such as the modeling of ecosystem processes or population viability analysis in ecology, and the modeling of the behavior and interaction of economic agents in economics. Furthermore, researchers in both disciplines have made attempts to integrate knowledge from the respective other discipline (Cooke et al. 2009). Agricultural economists, for example, integrate knowledge from the natural sciences when applying the production function approach, which requires natural science knowledge to quantify the impact of changes in the natural system on yield (cf. Brady et al. 2015 for an example). In the field of conservation biology, a prominent question is how to optimally allocate conservation reserves to maximize the number of protected species under a budget constraint, which is heavily based on the economic concept of cost-effectiveness (Kukkala & Moilanen 2013). While ecologists and economists do share a number of central concepts, researchers working in the field of governance typically rest on different concepts and address problems that cannot be easily captured by mathematical modeling or mathematical optimization. Hence, they apply different approaches such as qualitative research or statistical methods.

There are, however, concepts that may be shared by all three disciplines. One example is the concept of “tipping points”. This term was originally used in studies on racial segregation (Grodzins 1958). After publication of the book “The tipping point” by Malcolm Gladwell (Gladwell 2000), the use of the term in the scientific literature has multiplied. It is now mainly used by natural scientists, but the diverse examples given in Gladwell’s book, including fashion trends, crime rates and the financial crisis show that the concept is highly relevant for social scientists too (van Nes et al. 2016).

Researchers in the field of governance also work towards developing measurable proxies to evaluate certain governance structures that may be integrated in models. For instance, the governance aspect “bargaining power of farmer associations” may be expressed by the indicator “membership in farmer associations” which is easy to measure as a ratio of number of farmers that are members in a farmer association / number of farms * 100. This might be accompanied by measures on the importance of the agricultural sector in an economy (ratio of agricultural area / total area and agricultural employment / total employment, cf. Theesfeld et al. 2010). Similarly, according to Rabinowicz and Swinnen (1997), the use of the indicator “share of agricultural votes” can be used as an indicator to assess the bargaining power of farmers’ associations. Further, running an associations office in Brussels (“yes” or “no”) can be included as a binary variable to assess the same aspect.

In addition to the development of such quantifiable indicators, several other developments may facilitate the future integration of the governance subsystem in integrated models and the development of such models in general. First, there is an increasing use of agent-based models. These models are able to integrate knowledge from different disciplines and to capture ideas based on behavioral theories that go beyond profit-maximizing behavior of agents traditionally assumed in economics (Schlüter et al. 2017). This may lower the barriers for governance research towards participation in integrated modelling. Second, today many calls from funding agencies require an interdisciplinary consortium. In our opinion, this has helped, over time, to improve the understanding between disciplines, as only well-composed and balanced project proposals have a chance of being successful. Finally, it is our impression that younger researchers are more open and curious towards integrated research than previous researcher generations.

Despite the described challenges, we strongly argue for the development of complex models that combine the natural, economic and governance subsystems and include feedback loops, tipping points and cascading effects. Developing such models has the potential to greatly enhance our understanding of agri-ecological systems and our capability to address the huge challenges they face.

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