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Integrating Institutions into Bio-Economic Modeling for Development: A Background Paper for the IFPRI BioSight Project on Sustainable Agricultural Intensification at the Nexus of Food, Water, Land, Energy and the Environment

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Abstract

Policies that are successful in fostering sustainable intensification are critical to current development efforts to alleviate poverty and hunger and foster food security and resilience (The Montpellier Panel, 2013). BioSight is a globally integrated initiative coordinated by IFPRI that aims to contribute to such policies by developing a toolkit that offers high-quality ex ante decision tools, data, and evidence that is based on mathematical bio-economic simulation modeling calibrated to both temporal and spatial (field to globe) scales. It is envisioned that this toolkit would be used for policy analysis that might include ex ante assessment of the tradeoffs associated with policy alternatives in terms of the impacts of economic activity on the environment, impacts of environmental services on economic activity, impacts of environmental regulations on economic activity and well-being, and implications of scaling-up pilots.

Transactions between individuals and groups are at the core of economic activity that is based on natural resource use. Effective coordination of those transactions is necessary for achieving sustainable intensification for development, especially in ecosystems that are highly complex and interconnected (Hagedorn, 2008, 2013). Such coordination is provided by formal and informal socio-economic institutions, including regulations, bylaws and customs. One of the objectives of BioSight is to explicitly integrate these institutions into its mathematical bio-economic modeling framework.

In this paper, the work of agricultural systems modelers such as Ewart (2011) and Janssen and Ittersum (2007) is combined with analytical insights from institutional theorists such as Ostrom and Cox (2010) and Williamson (2000) to create an analytical framework of a social-ecological system that is consistent with both bio-economic modeling and institutional analysis approaches. Using that framework to structure a selective review of the literature on bio-economic models, we conclude that all bio-economic models have institutional foundations. The key questions are: (1) How explicitly are institutions depicted in the model?; (2) Is the model restricted to analysis of fixed aspects of institutions, or does it allow for the analysis of variable aspects, such as variable costs or the variable efficiency of institutions (e.g., transaction costs and imperfect monitoring)?; (3) Does the model allow for comparative analysis of different types of institutional contexts (e.g., unitary versus non-unitary households or open access versus private property)?; and (4) Does the model attempt to depict institutional change processes?

Drawing upon the analytical framework and literature review, the concluding section of the paper presents a summary of the different approaches to modelling institutions, and some of the tradeoffs associated with those approaches. Institutions can be modelled through their effects on: resources, constraints, marginal conditions, the structure of transactions or interactions between individuals, and/or as the outcome of social choice processes. There is no ‘right’ or ‘best’ way to integrate institutions into bio-economic models. All else equal, the best practice is to be explicit,

to clarify links between important policy choices and institutions, and to simplify complex institutions into model parameters that can be varied to depict alternative scenarios.

1) Introduction

Policies that are successful in fostering sustainable intensification are critical to current development efforts that seek to simultaneously alleviate poverty, foster food security, and enhance resource sustainability and resilience (The Montpellier Panel, 2013). BioSight is a globally integrated initiative coordinated by the International Food Policy Research Institute (IFPRI) that aims to contribute to such policies by developing a toolkit of high-quality decision tools, data, and evidence based on mathematical bio-economic modeling. It is envisioned that this toolkit will be used for policy analysis that might include ex ante assessment of tradeoffs associated with policy alternatives in terms of impacts of economic activity on the environment, contributions of ecosystem services to economic activity, effects of environmental regulations on economic activity and well-being, as well as the implications of scaling-up successful pilot activities on the sustainable intensification of larger systems.

At the center of economic activity that is based on natural resource use are transactions between individuals that need to be effectively coordinated, through incentives and constraints, in order for sustainable intensification to be achieved, especially for the case of ecosystems that are highly complex and interconnected (Hagedorn, 2008, 20013). Such coordination is provided by governance bodies and institutions--including formal regulations and laws as well as informal rules, norms, and conventions of accepted patterns of behavior. One of the objectives of BioSight is to integrate institutions into its mathematical bio-economic modeling framework.

This paper aims to contribute to BioSight through providing insight into the range of potential approaches to modelling institutions, and some of the tradeoffs associated with those approaches, as well as some best practices for the incorporation of institutions into bio-economic models. We proceed by, first, developing an analytical framework of a social-ecological system that is consistent with both bio-economic modeling and institutional analysis approaches. The foundation for the analytical framework is a modeling decision framework that builds upon the work of agricultural system modelers such as Ewart (2011) and Janssen and Ittersum (2007). On that foundation, we add components that capture key institutional, governance and policy issues, building upon analytical insights from institutional theorists such as Ostrom and Cox (2010) and Williamson (2000). The result is an analytical framework that depicts a wide array of possibilities for integrating institutional, governance and policy considerations into bio-economic models. Synergies and tensions in the alignment of bio-economic models and institutional analysis are explored through a discussion of nine key design features of bio-economic models.

This bio-economic institutional framework is then used to structure a selective review of bio-economic models that have explicitly integrated institutions. Rather than attempting a comprehensive review of those modeling efforts, we review twelve bio-economic models that have been implemented at various temporal and spatial scales, across various sectors, and employing various model types. We review models that depict interactions in various institutional settings (e.g., non-unitary households, collectives, social networks, and markets). And, we review models that depict common-pool property rights over various resources (e.g., rangelands and forests). We review models that link sub-system models, either through the use of a single linking model or an integrated framework. And, finally, we review a model that employs threshold analysis to choose the timing of policy change under uncertainty. This review demonstrates that there is a wide variety of ways in which modelers have explicitly integrated institutions into bio-economic models

From this review of bio-economic models that have explicitly integrated institutions and investigation of bio-economic models in which this has not been done, it is clear that all bio-economic models have institutional foundations. The key questions are: (1) How explicitly are institutions depicted in the model?; (2) Is the model restricted to analysis of fixed aspects of institutions, or does it allow for the analysis of variable aspects, such as variable costs or the variable efficiency of institutions (e.g., transaction costs and imperfect monitoring)?; (3) Does the model allow for comparative analysis of different types of institutional contexts (e.g., unitary versus non-unitary households or open access versus private property)?; and (4) Does the model attempt to depict institutional change processes?

Drawing upon the analytical framework and literature review, the concluding section of the paper presents a summary of the different approaches to modelling institutions, and some of the tradeoffs associated with those approaches. Institutions can be modelled through their effects on: resources, constraints, marginal conditions, the structure of transactions or interactions between individuals, and/or as the outcome of social choice processes. There is no 'right' or 'best' way to integrate institutions into bio-economic models. All else equal, the best practice is to be explicit, to clarify links between important policy choices and institutions, and to simplify complex institutions into model parameters that can be varied to depict alternative scenarios.

2) Definitions and Scope

2.1 Sustainable Intensification in Agricultural Systems

In order to meet the increased demand for food required by increasing populations, increasing affluence, and the alleviation of poverty-induced hunger, humanity will need to increase production of all major food crops and animal and aquaculture products between 50% and 100% by 2050; that will need to be done in a sustainable way, without expansion of cropland at fragile extensive margins or otherwise taxing the globe's ecosystems (Brundtland, 1987; Daina et al., 2013; Godfray et al., 2010; Royal Society, 2009). Since this production increase needs to be rapid and will involve complex interrelationships between systems, it needs to be well regulated. This will require coordinated policy interventions, at the core of which will be policies that shape the incentives and constraints of individual producers, marketers, and consumers (Barrett et al., 2004; Godfray et al., 2010; Herrero et al., 2010; McDermott et al., 2010).

In the past, increases in food production typically involved tradeoffs between investments in physical capital (e.g., techniques, tools, and infrastructure) and divestments in natural capital. The sustainable intensification that is required for the future will involve producing more food from the same amounts of land and water while reducing environmental impacts, requiring investments in all forms of capital -- physical, natural, financial, human, and social (Bresser and Millonig, 2003; Dorward et al., 2004; Pretty 2008). Some increases in food production will be multiplicative, achieved by increased productivity of current crop, tree, livestock and fish enterprises through the combined use of new and improved varieties and approaches to agronomic and agro-ecological management. Other increases will be additive, based on increased diversification by the use of new crops, trees, livestock, and fish. Successful pilot experiments where sustainable intensification has already occurred need to be implemented at larger scales and lessons spread; new multiplicative and additive solutions will also be needed (Pretty et al., 2011).

Sustainable intensification will thus require a coordinated and targeted increase in innovation in techniques, management systems, governance arrangements, and institutions, as well as policies that fit diverse farming systems, governance contexts, and phases of agricultural development (Dorward et al., 2004). In order to achieve the broader development goals of poverty and hunger alleviation as well as increased food security and resilience, a major emphasis in sustainable intensification will need to be placed on resource-poor small-holder farmers in developing countries. Better models are urgently needed that can more accurately predict the complex interactions that this will involve, and provide ex ante guidance of the 'best bet' portfolios for a variety of situations among the various policy options in terms of investment (e.g., infrastructure, technology, land reform, governance, social safety nets, jump starting local input/output markets, and value chain market development) and instruments (e.g., regulatory, market (dis-)incentive based, and facilitated-voluntarism (e.g., extension)) (Dorward et al., 2004; Ewart et al. 2011; Garnett and Godfray 2012; Hagedorn, 2008; Herrero et al., 2010).

2.2 Role of Institutions in Sustainable Intensification

The success of any policy to support sustainable intensification will depend upon governance bodies (i.e., inter-governmental organizations, governments, private firms, cooperatives, collective action groups, informal networks, and households) and their institutions that provide incentives for and constraints on production, marketing and consumption behavior. Institutions can broadly be defined as the formal policies, directives, and laws of governance bodies as well as the informal commonly-accepted rules, practices, and norms that together establish expectations regarding transactions. They are used by governance bodies to provide coordination, reduce conflict, and increase mutual benefit for their members through guidance and regulation of transactions. At another level, institutions are also used by governance bodies to define and evaluate themselves in terms of their membership and roles in institutional choice, monitoring, and enforcement (Barrett, 2008; Fulginiti et al., 2004; Meinzen-Dick and Pradhan, 2002; Newton et al., 2013; Williamson, 2000).

Institutions perform multiple functions in the process of sustainable intensification. Insights into these roles are provided by the fields of new institutional economics--with its consideration of informational asymmetries, the costs of transactions between individuals, and the costs of governance itself (Dorward et al., 2004; Kherallah and Kirsten, 2001)--and behavioral economics--with its consideration of imperfect information, fairness, loss aversion, and intrinsic motivations for individual decision making (Camerer and Loewenstein, 2004).

The primary processes of food production are highly dependent on natural resources, involving transactions in the processes for accessing inflows of goods and services as inputs and converting production outputs into outflows of benefit streams. Institutions support these transactions to such an extent that conceptually, natural-resource based production and marketing processes and their corresponding governance and institutional supports can be characterized as finely-matched techno-institutional regimes (Hagedorn, 2008; Ostrom and Cox, 2010).

The close connection between the biophysical-technical and institutional aspects of natural-resource based production and marketing processes has led theorists to hypothesize that the nature of transactions is shaped to a large extent by the biophysical-technical characteristics of either the good or service being transacted over or the ecosystem that produces it. Key characteristics of a good or service are its excludability and rivalry of consumption, with different governance structures ideally suited for each of the four combinations of these characteristics as follows: (1) excludable-rivalrous private goods – best governed by the market (e.g., inorganic fertilizers); (2) non-excludable-non-rivalrous public goods – best governed by the government (e.g., major transportation routes, amenity value of the rural landscape, and biodiversity); (3) non-excludable-rivalrous common-pool goods – best governed by collective action groups (e.g., common pasturelands, fishing grounds, and forests); and (4) excludable-non-rivalrous goods – best governed by the government if any governance is necessary (Coase 1960; North 1971).

Institutional economists have also considered the institutional implications of a good or service's ecosystem of origin. Swallow and Meinzen-Dick (2009), for example, consider the factors that affect ecosystem service markets in terms of function and participation, including key "partner resources" for ecosystem service supply, such as wetlands, riparian areas, and corridor areas. Because the possibility for private exchange over ecosystem services is often constrained by the nature of these key partner resources, partner resources themselves may be best suited to management in the public domain, while some of the ecosystem services that they generate may be suitable for private transactions. Hagedorn (2008) focuses on two key characteristics of ecosystems (coupled with supporting infrastructure) as shaping transactions: their degree of modularity or decomposability, and the functional independence of biophysical processes. Different types of transactions are associated with the four combinations of these characteristics: (1) modular/decomposable and functionally independent ecosystems – allowing for atomistic-isolated transactions; (2) modular/decomposable, but functionally interdependent ecosystems – may require atomistic-interconnected transactions; (3) non-modular/decomposable, but functionally independent ecosystems – requiring complex-isolated transactions; and (4) non-modular/decomposable and functionally interdependent ecosystems – requiring complex-interconnected transactions (Hagedorn 2008, 2013) [1].

For both transactions over excludable-rivalrous goods and services and those that are atomistic and isolated, transaction costs are relatively low, such that a market governance structure, backed by government support, such as grading and enforcement, may be sufficient. On the other hand, for both transactions over non-excludable-rivalrous goods and services and those that are complex and interconnected, transaction costs tend to be relatively high, such that a market governance structure is not likely to be sufficient. In these cases, a collective-action based governance structure, again backed by appropriate government support, tends to be in order.

Both market and collective-action governance structures are extensively supported by institutions. Market transactions need to be supported by institutions that: define and uphold rights to private goods and services (e.g., property rights and land tenure institutions) (Angelsen, 1999; Besley, 1995; Meinzen-Dick and Pradhan, 2002); define the markets themselves (e.g., partnerships, bi-lateral contracting, value chains, etc.) (Barrett, 2008); and reduce inefficiencies that result from market exchanges that do not fully account for informational asymmetries, transaction costs (i.e., information, contract negotiations, and contract enforcement), or externalities.

Collective-action governance entities use institutions to support transactions over common-pool goods and services and transactions that are complex and interconnected. Collectives can also use institutions to perform several functions that allow smallholders to remove market entry

[1] These two criteria capture a range of properties of transactions important for matching them with appropriate institutional and governance support: excludability and rivalry of consumption, asset specificity, frequency and uncertainty, jointness and separability, coherence and complexity, standardizability and calculability, dimensions of time and special scales, predictability and irreversibility, spatial characteristics and mobility, adaptability and observability (Hagedorn 2008).

barriers associated with their scale of operation: redistributing property rights; replacing missing markets for information, risk management, and micro-financing; and reducing transactions costs, including costs associated with the uncertainty of transactions (Bhattamishra and Barrett, 2010; Cavatassi et al., 2012; Hagedorn, 2013; Meinzen-Dick et al., 2004; Poteete and Ostrom, 2004).

The close relationship between the biophysical-technical characteristics of natural-resource based production and marketing processes and the required institutional support means that institutions both shape the range of production and marketing possibilities, in terms of incentives and constraints, and institutions themselves are shaped by production and marketing processes. Often a change in a natural-resource using production or marketing technique requires *ex ante*, or *ex post* creates demand for, change in the techno-institutional regime (Hagedorn, 2008; Ostrom and Cox, 2010). This process of change is complex, path dependent, and involves time lags. Whereas institutions themselves are public goods (within the relevant group), their creation, maintenance, implementation, and change tends to be costly in terms of both real and transaction costs to both individual members and the group as a whole.

Finally, the strength of an institution is dependent on the strength of the monitoring and enforcement capacity of the implementing governance body, which is in turn dependent on the relationships with the governance bodies in which the original governance body is nested. Thus, effective integration among the institutions of the various governance bodies is key, whether between communities, collective action groups and government, levels of government, or public and private sectors (Barrett et al., 2004; Coase, 1960; Hagedorn, 2008; Ostrom and Cox, 2010; Rustagi et al, 2010). Given the vast diversity of both biophysical-technical imperatives of natural-resource based production and marketing processes and governance and institutional contexts, what is needed for sustainable intensification is an approach that is flexible and adaptable, and focused on establishing cooperative partnerships (Barrett et al., 2004; Behere and Engel, 2006; Herrmann et al., 2011; Ostrom, 2007).

2.3 Sustainable Intensification in the Developing Country Context

There are some unique and somewhat generalizable characteristics of agriculture and natural-resource use in developing countries, as well as the resource-poor smallholder producers in these contexts, that should be considered in the design of policy to support sustainable intensification. These characteristics tend to place specific demands on the governance and institutional components of such policies.

Like their counterparts in more developed countries, developing country producers tend to be optimizers and reasonably rational, once all constraints are taken into account (Brown, 2000). However, developing country farmers often make their production decisions by balancing the interests of more inter-related actors, both within and outside the household, and considering more inter-related goals and constraints. This tends to increase the degree of heterogeneity of actors and outcomes, and the number of interactions and transactions among actors. Some of the characteristics of complex ecological systems thus apply equally to developing country farming systems: a low degree of modularity and decomposability of structures and a high degree of functional interdependence of processes (Hagedorn 2008)[2].

Specifically, the developing country context is characterized broadly as having challenges in ago-ecology, economics, and policy, many of which originate in poverty and resource scarcity that leads to the use of more marginal livelihood strategies. Compared to those located in developed countries, a greater number of farming systems located in developing countries are more closely integrated with natural, complex eco-systems. And, soils in many tropical areas-– particularly in semi-arid parts of Africa, India and Brazil--tend to be highly fragile, susceptible to irreversible changes, and highly variable in quality (Eswaran, Lal and Reich, 2001; Tittonell et al., 2007). Developing country farming systems tend to be rain-fed, which contributes to their high variability, risk and uncertainty.

Developing country economies tend to be dominated by a large subsistence agricultural sector, very weak formal non-agricultural sectors, and rapidly growing populations. The subsistence sector tends to be remote from central cities and poorly serviced by infrastructure, such that it mainly operates at a 'low input-low output' level (Dorward et al., 2004; Tittonell et al., 2007). Production and marketing costs are high, including both real and transaction costs, such that there are multiple missing markets, especially for financial capital, like insurance and credit. And, food grain and input markets tend to be thinly traded and imperfect (Barrett and Mutambatsere, 2005). This can create expectations of low profits from intensification. Lack of formal markets means that many transactions over inputs and outputs are informal, and social and economic systems are closely integrated (Bhattamishra and Barrett 2010; Hogset, 2005). Complex household structures mean that within any given household there are often multiple decision makers with divergent goals and constraints, as well as close connections between production and consumption decisions and production and care responsibilities.

Finally, some of the unique characteristics of developing countries' policy processes have implications for the process of sustainable intensification. Developing country governance systems tend to be diverse and overlapping; many are undergoing various forms of decentralization (Agrawal and Ostrom 2001). And, the very nature of being at lower stages of socio-economic development means that it is likely that the policies necessary to support sustainable intensification will be challenging to implement. Given that less conducive farming conditions imply the use of a wider and more variable set of strategies to achieve more diverse goals, farm management recommendations for sustainable intensification in developing countries

[2] Poteete and Ostrom (2004), for example, state that "[u]sers of forestry resources are interacting with complexly, adapting ecological systems and are themselves a part of a human, complex, adaptive system. Both ecological and human systems exist at multiple scales over time" (p.228). They note that this makes attempts to build systematic knowledge about collective action in various contexts "extremely challenging puzzles".

are likely to be more strategic than prescriptive (Tittonell et al., 2007). And, it is likely that different policies will be needed to support sustainable intensification at different stages of agricultural and non-agricultural sector development[3]. This would mean that national policies might need to be nuanced and flexible across time, and differentiated by areas of agro-ecological potential, and therefore, in some cases, administrative area (Dorward et al., 2004).

2.4 Bio-Economic Models

Bio-economic simulation models can be used to address this need for both greater conceptual understanding of the complex and dynamic processes involved in sustainable intensification and a more fine-tuned and effective toolkit to generate and evaluate policy options. This toolkit is needed for policy analysis that might include ex ante assessment of the tradeoffs associated with policy alternatives in terms of the expected benefits and costs of the impact of economic activity on the environment and states of environmental services and environmental regulations on economic activity and well-being, as well as the implications of scaling up successful pilots of sustainable intensification. Such assessments would help to reduce the costs of policy change by reducing uncertainty and increasing the likelihood of policy efficacy and efficiency by identifying the "best bet" policy options (Whitten and Bennett, post 2004).

Bio-economic models integrate simulations of biophysical-technical and agro-ecological processes with economic optimization processes. They allow comparisons of alternative states of ecosystems associated with various states of climate variability, technological innovation, and policy options in terms of impacts on future flows of benefits and costs. Generally, the foundation of the economic component of bio-economic models is the neoclassical perfect market model with its assumptions of autonomous, rational, and optimizing unitary households as actors, only private goods with fully-defined property rights, zero externalities, zero informational asymmetries, and zero transaction costs, including costs for information access, contract negotiations, and contract enforcement. Under these assumptions, markets exist for all goods and services, and spatial variation in economic behavior only depends on biophysical-technical and agro-ecological processes and resources. Most of these models assume that the institutions and policies that bring about these conditions are fixed and exogenously determined.

Some examples of complex system models that have been used for bio-economic modeling are standard optimization, Bayesian network, systems dynamics, evolutionary, and agent-based models (Heckbert et al., 2010). Using such models, policy analysis consists of analyzing and

[3] Dorward et al. (2004) hypothesize three broad stages of public investment development: laying the foundations of markets (e.g., development of physical capital—infrastructure and technology--and land reform), kick starting markets (e.g., extension and extensive support of local input and output markets, especially seasonal finance), and support of the private sector.

comparing the benefits and costs[4] associated with alternative policy options, including implications for resource stocks. Scenario analysis can be employed to explore the impact of policy options on various system states. Sensitivity analysis can be employed to identify critical parameter values, and to assess the sensitivity of model outcomes to changes in key parameter values (Whitten and Bennett, post 2004). The implications of various exogenous factors and stochastic events are included in the analysis. Bio-economic models are designed at various scales, both spatially, from field to globe, and temporally, from a year to centuries (Brown, 2000). Although bio-economic models can generate socio-economic information beyond the absolute benefits and costs associated with various policy options, such as potential distributional impacts, this has not been an emphasis (Prellezo et al., 2010; Whitten and Bennett, post 2004).

One tension for all modeling processes is choosing the level of complexity of the model to balance performance criteria-- relevance, comprehensiveness, transferability, and policy impact-- with the operational demands of greater complexity, in terms of data and indicator collection and management as well as the difficulty of efficiently and effectively managing a complex model (Brown, 2000; Heckbert et al., 2010; Janssen and van Ittersum, 2007a; Prellezo et al., 2010). Nevertheless, at the forefront of bio-economic modeling are attempts to find modeling solutions that allow such increased performance.

Modelers are attempting to increase the relevance of their outputs--the closeness-of-fit with reality in terms of specification of the objective function, decision-making processes, constraints, activities, and coverage of dynamic aspects--by comparing model outcomes with empirical findings. An example of a model modification designed to increase relevance is the relaxation of the assumption of perfect information on the biological side of a model to address information-scarce situations which produce risk and uncertainty, for example, of potential ecosystem responses to changes in management and stochastic events, such as climate variability (Keating et al., 2013). An example of such a modification on the economic side of a model is to incorporate trade-offs among multiple objectives of producers such as maximizing productivity and minimizing land degradation (nitrogen loss) (Tittonell et al., 2007).

Modelers are attempting to increase the comprehensiveness of models through incorporation of factors such as: new functions of the agricultural sector such as enhancement of rural landscapes in developed countries and protection of biodiversity in all countries; psychological, cultural, social, and political factors as well as the socio-economic institutions that affect producer decision-making; and policies based on persuasion of voluntary action (e.g., extension) rather than just policies based on regulation (e.g., zoning and quotas) and market (dis-)incentives (e.g., taxes and subsidies). Some of these modifications are challenging modelers to find ways to incorporate into bio-economic models qualitative in addition to the standard quantitative data

[4] Benefit-cost analysis allows a means of measuring, grouping and comparing disparate factors in a common (monetary) unit, and then analyzing the marginal benefits and costs of alternative policy options (Kragt et al., 2010).

(Borges et al., 2011; Janssen and van Ittersum, 2007). Issues of transferability of models or findings are especially acute for models designed within a developed country context vis-à-vis a developing country problem situation. Transferability is also important for models designed to guide the process of scaling up successful pilots of sustainable intensification. One possible route for increasing transferability is to develop specific modules and aggregation algorithms applicable to various specific contexts that are themselves flexible and can be flexibly inter-linked. Finally, at the frontier of bio-economic modeling are also attempts to increase the ownership of the outcomes of modeling efforts by making the modeling process itself more participatory for producers, stakeholders, and policy makers (Borges et al, 2011; Herrmann et al., 2011; Janssen and van Ittersum, 2007; Mongruel et al., 2011; Van den Belt, 2004).

3) Conceptual Framework and Approach

This section presents an analytical framework of a social-ecological system that is consistent with both a bio-economic modeling and an institutional analysis approach. The foundation for the analytical framework is a modeling decision framework that builds upon the work of agricultural system modelers such as Ewart (2011) and Janssen and van Ittersum (2007). On this foundation, we add components that capture key institutional, governance and policy issues, using analytical insights from institutional theorists such as Ostrom and Cox (2010) and Williamson (2000). The result is an analytical framework that depicts a wide array of possibilities for integrating institutional, governance and policy considerations into bio-economic modeling. The following section of this paper reviews selected studies that have attempted to implement some of those possibilities.

3.1 Key Elements of a Bio-Economic Modeling Approach

Figure 1 depicts the structure of a generic bio-economic model that illustrates the standard elements and logical connections of bio-economic models. Please note that Figure 1 is scale neutral such that it is applicable to any spatial scale, from plot to globe.

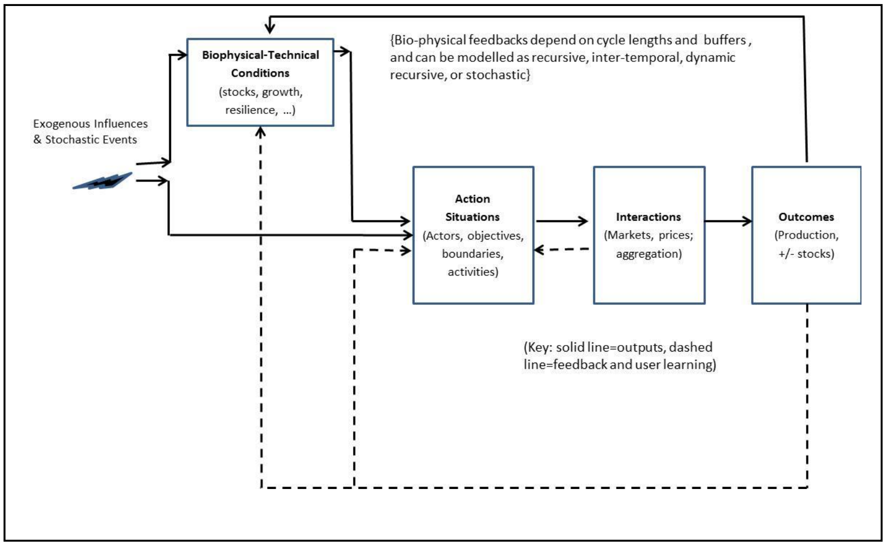

Figure 1 Depiction of the structure of a generic bio-economic model (Source: Authors)

It can be seen from Figure 1 that developing a mathematical model to represent the complex reality of biophysical-technical and economic processes would involve decisions about several model components:

1) Resources–the baseline resources and biophysical-technical opportunity set that is available to the operational unit. This can be considered as types of capital: natural, physical (including infrastructure and techniques), financial and human capital. The modeler specifies and measures these in terms of stocks, buffers, flows, and/or potential break-points or thresholds. The modeler chooses how these are defined.
2) Activities—the actions taken by the operational units and the way that those actions are depicted viz-a-viz time
   a. Defining the activities undertaken by the operational units--the biophysical and/or technical processes by which inputs of natural resources, energy, physical capital, labor, and management are combined through resource management, investment, production, and marketing processes to create outputs/benefits and impact on natural resource stocks;
   b. Process of change—depiction of the process of change (e.g., static or dynamic--recursive, inter-temporal, dynamic recursive, or stochastic);
3) Constraints—the technical and accounting constraints that limit the operational unit(s) in attaining their objectives (e.g., endowments, biophysical-technical feasibility, and prices);
4) Operational units–the units that undertake activities and make decisions:
   a. Defining the operational unit (e.g., a household or farm manager);

b. Objectives—normally single objectives, but can be multiple (e.g., increasing consumption, profits, market share, or bargaining position, or minimizing the use of a scarce form of capital, like land or labor);
c. Motives and incentives–the intrinsic motivations and extrinsic incentives that drive choice processes (e.g., profit maximization or cost minimization);
d. Choice process—optimization (e.g., maximizing the present value of a stream of expected future income);

5) Interactional Considerations—inter-temporal (e.g., crop rotations, livestock herd effects), inter-spatial (e.g., between adjacent fields, farms or systems), combined inter-spatial and inter-temporal (e.g., tree-crop interactions in agroforestry systems), inter-enterprise (e.g., crop-livestock/aquaculture and crop-tree), and intra-eco-system/enterprise (e.g., competition for light, water and nutrients);

6) Outcomes—the outcomes of the operational unit(s)' activities and their direct consequences (e.g., production and changes in the stocks of resources);

7) Scale Issues and Aggregation:
   a. Scale Issues
      i. Spatial Scale—the spatial distinctions relevant to the various biophysical-technical and economic processes and their consequences (e.g., field to globe);
      ii. Boundaries--the boundaries of the system within which operational units implement activities (e.g., a river basin);
      iii. Temporal Scale/Cycle Length--the biophysical-technical and economic time-step within which choices are made and consequences are realized (e.g., reproductive season in livestock or aquaculture systems; annual cropping cycle in a unimodal rainfall context; tree planting to harvest; and time between purchase of inputs and realization of income);
   b. Aggregation—the ways that operational units' activities are aggregated across time and space (e.g., fields into farms, years into decades, farm enterprises into farms, and farm output into market supply);

8) Sources of Variation, Risk and Uncertainty—the sources of variation, risk and uncertainty that the operational unit(s) knowingly or unknowingly face;
   a. Endogenous Sources—sources internal to the system (e.g., eco-system, human health, production, investment, marketing, and market prices for certain outputs; especially, resource stability--concerns to minimize fluctuations in harvesting possibilities);
   b. Exogenous Sources--the external influences and stochastic events that affect the state of the natural resource, the operational unit(s)' decision context, and production and marketing activities, but are not affected by those activities (e.g., climate, weather, pests and diseases, global economic downturn, and market prices for agricultural inputs and certain outputs);

9) Impact Pathways and Externalities--the way that the actions of operational units generate consequences for those both inside and outside the system (e.g., changes in the quality of water available to downstream water users); and
10) Feedbacks--the feedback or updating mechanisms by which actions and exogenous factors from one period feed forward into changes in base conditions in the subsequent period, as well as the flows of information about those feedbacks (e.g., increases or decreases in stocks of natural resources and income) (Borges et al., 2011; Brown, 2000; Ewert et al., 2011; Janseeen and van Ittersum, 2007; Prellezo et al., 2010).

These key elements of bio-economic models are summarized in Table 1 and explained in further detail in the remaining sub-sections of Section 3. A plus sign in the columns on the right of Table 1 indicate that the characteristics from the column(s) to the left are included. The asterisk in the economic column indicates that although the neo-classical perfect market model is the core, some bio-economic modelers have relaxed some assumptions to bring in aspects of institutions in order to make their models more useful for policy analysis.

3.2 Depicting Spatial Scale, Boundaries, Temporal Scale, and Aggregation in Bio-Economic Models

Figure 2 is based on Ewert et al. (2011) and illustrates four of the key decisions made in the construction of bio-economic simulation models: spatial scale, boundaries, temporal scale (cycle length), and aggregation in both spatial and temporal scales. The vertical axis in Figure 2 depicts the spatial extent of the system, which can range from plot, farm, region, and all the way to the full global scale (especially for climate models). Modeling decisions about spatial extent imply decisions about boundaries between units: a plot may be physically bounded by a fence, a river basin catchment by a hillslope and its drainage, and a province by the authority systems of administrative–political jurisdictions.

The vertical arrows in Figure 2 illustrate the process of aggregating or upscaling of the spatial extent of a model by, for example, combining results from plot-level models to represent whole farms, or combining results from region-level models to represent whole nations. The simplest approach to spatial aggregation is to assume a linear relationship, and simply sum results from models of lower-level units. Often, however, model builders identify important emergent properties or non-linearities that should be considered as they expand spatial scale.

This happens, for example, in scaling up soil processes from plot to farm level, because at the plot scale it may be sufficient to equate soil erosion with soil detachment, while at the catchment level it becomes more important to consider the ways that detached sediment moves from erosion source to sediment deposition areas. An example from the economic side of bio-economic models is the market prices of agricultural products: it is usually appropriate to assume that the output from an individual farm will have no effect on the market price of the product, while simultaneous increases in output from a number of farms in a region are likely to cause reductions in prices across the region. Non-linear aggregation may also be appropriate for depicting economies of scale in production or marketing, where more efficient use of inputs is achieved when more plots are cultivated or outputs marketed together.

The horizontal axis in Figure 2 depicts the temporal scale or cycle length, ranging from an annual cycle (e.g., production of annual crops in a rainfed cropping system with unimodal rainfall) to decades (e.g., production of timber trees), to centuries (e.g., soil formation and global bio-geo-chemical cycles). The horizontal arrows in Figure 2 illustrate temporal upscaling. A temporal upscaling from the annual to the decadal scale may be involved in modeling agroforestry systems, for example, that involve both annual production systems producing a series of crop outputs in annual time-steps and perennial production systems that produce timber outputs in decadal time-steps. The diagonal arrows in Figure 2 indicate ‘functional’ upscaling, that is, more complex interactions between spatial and temporal time steps (e.g., soil erosion within a year in an upstream farm may affect downstream residents several years later).

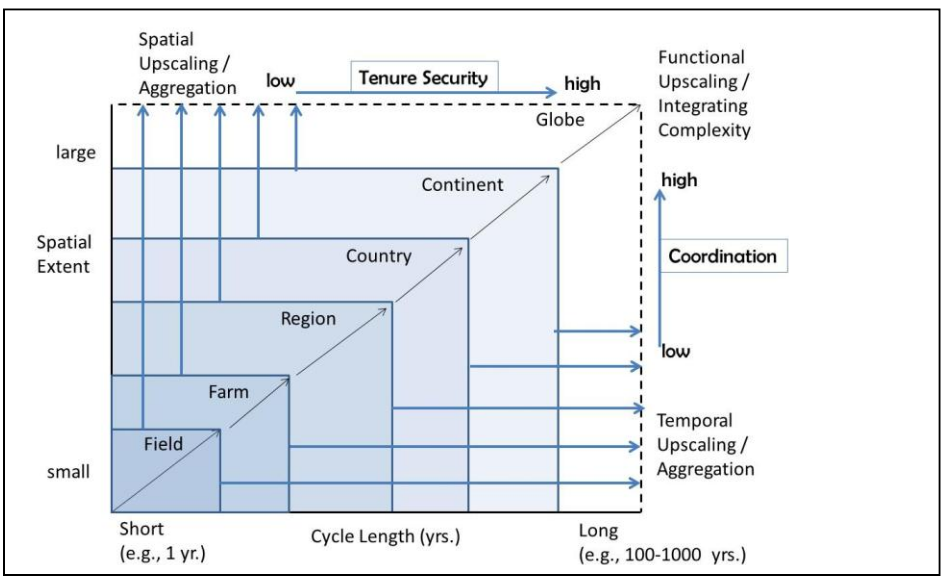

Figure 2 Depiction of the scales and levels of organization of a bio-economic model (Source: Ewert et al., 2011, p.7)

3.3 Depicting Dynamic Processes in Bio-Economic Models

Figure 3 depicts four ways that bio-economic models deal with time in terms of both production activities and feedbacks. The horizontal line depicts the passage of time, and the vertical hash lines depict specific periods of time, or cycle lengths, as discussed vis-a-vis Figure 2. A recursive model assumes that the decision maker considers each time period separately, such that the ending values for each period become the starting values for the subsequent period. An inter-temporal model assumes that the decision maker considers all time periods at the beginning, discounting future costs and revenues with a fixed discount rate. A dynamic recursive model also assumes that the decision maker considers the series of future time periods at the beginning; however in this case, the decision maker recognizes that the ending values from one period feed forward to become the starting values for subsequent periods. And, a stochastic model maintains the assumption that the decision maker considers the series of future time periods at the beginning, and models the way that the decision maker updates decisions during the time period to account for new information (e.g., weather outcomes) that becomes available during each sub-period (Jansen and van Ittersum, 2007).

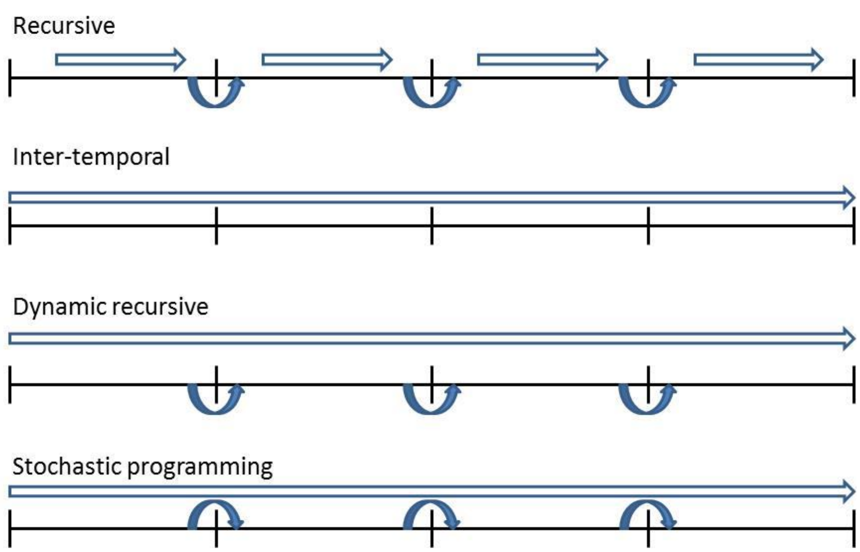

Figure 3 Alternative depictions of the temporal aspects of dynamic processes in bio-economic models (Source: Janssen and van Ittersum, 2007, pp. 628-629)

3.4 Matching Key Elements of Institutional Analysis with those of Bio-Economic Modeling

To various extents, the key elements of institutional analysis can be framed in ways that are aligned with bio-economic modeling, illustrating different ways that institutions can potentially be incorporated into bio-economic models. In this section, we draw upon the literature of new institutional economics (Williamson, 2000), institutional analysis for development (IAD) (Ostrom, 2000), and the more recent work on social-ecological systems (SES) (Ostrom 2009, 2011).

Figure 4 is a conceptual model that depicts the various linkages between the elements of bio-economic models and institutions. The foundation of Figure 4 was previously presented in Figure 1—the four top-most horizontal boxes and their linkages--which depict the links between Biophysical-Technical Conditions, Action Situations, Interactions, and Outcomes, as well as feedbacks and user learning from Outcomes to Biophysical-Technical Conditions and Action Situations. The set of three vertical boxes on the left side of Figure 4 depict the factors that shape Action Situations and Interactions: Biophysical-Technical Conditions, Community Attributes, and Williamson's (2000) four levels of Institution Conditions. Socio-economic feedbacks occur between Outcomes and Action Situations, and between Outcomes and the combined Biophysical-Technical and Institutional Conditions. The following sub-sections describe the ways in which the key elements of institutional analysis can be matched to the key elements of bio-economic models as listed in Section 3.1. These are summarized in Table 1.

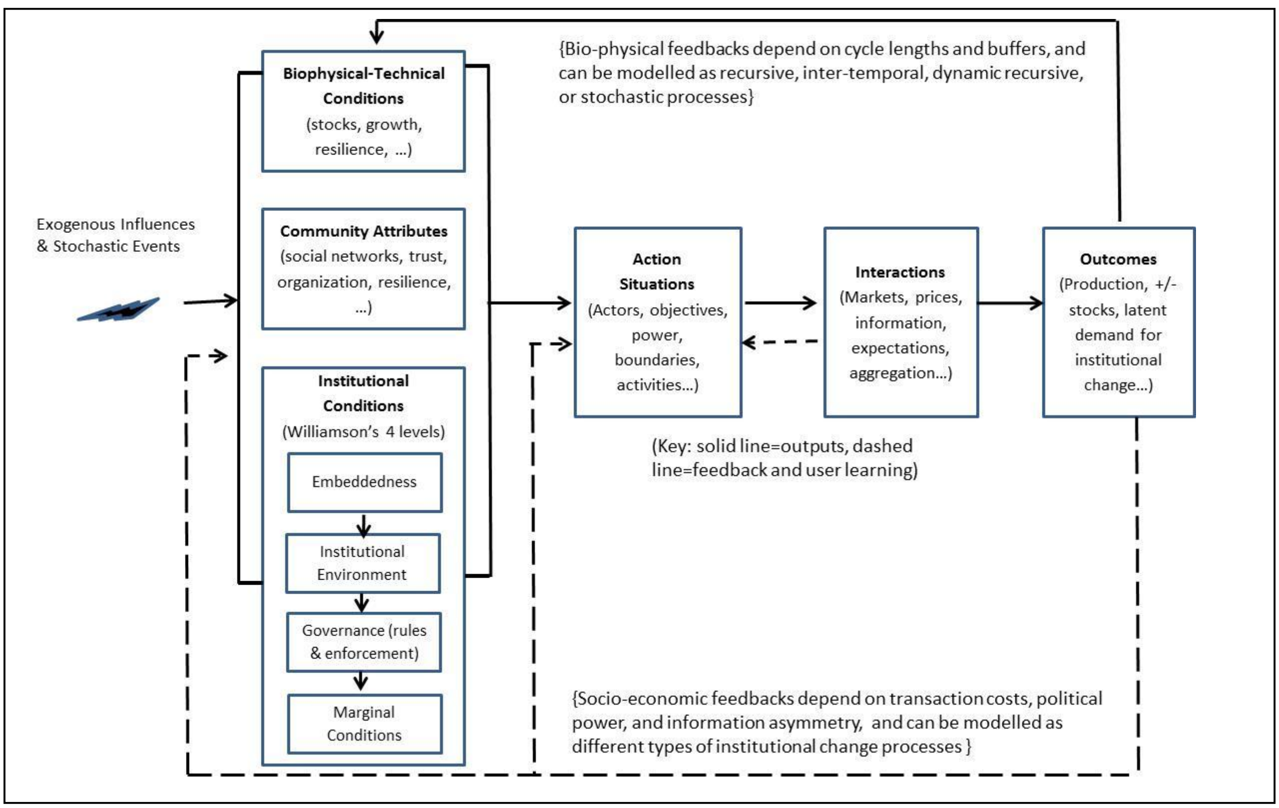

Figure 4 Bio-economic institutional model (Source: Based on Ostrom and Cox (2010) and Williamson (2000))

3.4.1 Resources

There are both similarities and differences in the ways that resources are depicted in bio-economic models and institutional analysis. Bio-economic models tend to focus on the stocks and flows of natural resources (i.e., natural capital), as well as physical, financial and human capital. Institutional studies also consider these factors, however, they tend to take a more holistic approach to choosing the types of 'resources' under consideration. The norm is to consider five types of capital–natural, physical, financial, human, and social--as first proposed by Chambers (1987) in the sustainable livelihoods framework.

Some would consider institutions as represented by social capital. Pretty et al. (2011) distinguish between different types of social capital—bonding among homogeneous individuals, bridging between heterogeneous individuals, and linking to vertical spheres---and they propose that individuals and groups benefit from having a balance of these different types of social capital. Baumans (2000) and others, however, have proposed the need to add a sixth type of capital – political capital--while others discuss the concept of institutional capital. Bresser and Millonig (2003) consider institutional capital from the perspective of strategic business management, defining institutional capital "as the specific conditions in an organization's internal and external institutional context that allow the formation of competitive advantage" (p. 229). They distinguish three main types of institutional capital: cognitive capital of the individuals who make up the organization; normative capital at the intra-organizational level; and regulative capital at the inter-organization level.

Thus, one obvious way to integrate institutions into bio-economic models is then to modify them to incorporate social, political and/or institutional capital. This would require specification of a quantitative representation of the stocks of these types of capital, their impact on production processes, and finally the feedback of outcomes on stocks.

3.4.2 Activities

a) Defining the Activities of Operational Units

In bio-economic models, the biophysical-technical activities of interest are the production and marketing processes, and the important economic aspects are choice of enterprise and technique, quantities of inputs and their allocation across enterprises, sequencing of activities, allocation of output between consumption and marketing, and savings and investment. In institutional analysis, the activities of interest center on transactions and actors' efforts to change institutions and policy. Of particular importance are the real and transaction costs of institutional and policy change.

There are several theories about actors' motivations for seeking institutional change. The needs-response (or setting dominant) theory stipulates that new policies and institutions emerge in response to certain needs or substantive aspects of a problem, with more severe needs being more likely to prompt distinct policy responses. For example, a dramatic flood event can prompt very rapid changes in government policy toward land use planning in flood-prone areas. The problem may prompt a response from a particular policy maker either directly or indirectly, through pressures exerted by the citizenry (Ciorcirlan, 2008). A similar situation can also occur in social institutions, such as those influencing gender roles. For example, the primarily subsistence farming women in some Cameroonian villages started cultivating rice for the market after the national economic crisis of the early 1990s (Fonjong and Athanasia, 2007). The theory of induced institutional innovation (Ruttan and Hayami, 1984) is a variant of the needs-response theory. It focuses on the demand for institutional change that is induced by changes in resource scarcities or endowments that drive demand for technique change. Anderson and Hill (1975) provide an example of the use of the induced institutional innovation theory to study the supply and demand for change in property rights over water in the United States.

Other theories of institutional change focus more attention on the processes by which groups articulate demands for institutional change through social and political processes, and politicians and governments respond to those demands. The interest group influence theory (Ciorcirlan, 2008; North, 1994) proposes that interest groups form to advocate for or against policy changes that further their economic or social interests; the interplay among those groups determines the policy outcome. The theory of economic rent seeking applies the same logic of utility or profit maximization to institutional change. That is, economic agents directly and indirectly attempt to influence government to impose regulations that will increase their benefits or decrease their costs. For example, agents might want to enhance the ability of their business to extract economic rents from consumers (Kruegar, 1974). A rent-seeking society is one in which this type of behavior becomes pervasive such that it is a major impediment to economic efficiency. Activities to change institutions can be integrated into bio-economic models, for example, by accounting for the monetary and transaction costs that institutional change requires of individuals and groups.

b) Process of Change

In bio-economic models, the dynamic aspects of the biophysical-technical production process are modeled in one of four ways: recursive, inter-temporal, dynamic recursive, or stochastic. Dynamic aspects of the economic side of the bio-economic model include marginal changes in intensity of activities, as well as decisions to begin and stop activities. Institutional analysis encompasses both of these changes, and adds to dynamic aspects responses to needs and the fixed transaction costs of institutional and policy change. Several models of institutional and governance change have been proposed. For example, Hagedorn (2008) analyses institutional change through a transaction-interdependence cycle. And, Westley et al. (2013) offer a theory of the transformation of governance systems through institutional entrepreneurship that adapts to the opportunities that arise in the various phases of an adaptive governance cycle of a resilient social-ecological system.

3.4.3 Constraints

Bio-economic models typically include as constraints endowments of capital (natural, physical (including infrastructure and technical options), financial and human), biophysical-technical feasibility, and prices. Some bio-economic models, although based on perfect market assumptions, include some institutional aspects in order to analyze the impact of policy change, such as quotas and zoning regulations and taxes and subsidies that shape the marginal conditions facing units. Institutional analysts would also add to constraints other types of formal and informal institutions, some of which might be expressed in bio-economic models as fixed rules.

3.4.4 Operational Units

a) Defining Operational Units

Similar to bio-economic modeling, institutional analysis is concerned with identifying the "actors" who are the direct decision-makers involved in production and/or marketing processes (e.g., tenant farmers). However, in bio-economic models, it is usually assumed that such actors make their decisions autonomously using price and other information, without regard to other stakeholders, and that the actors are relatively homogenous. In contrast to bio-economic modeling, institutional analysis gives greater attention to other actors who also influence outcomes (e.g., the household heads of subordinate household members), and other "stakeholders" who are affected by and therefore have interests in those production processes and their outcomes (e.g., landlords). Also, institutional analysts often focus on situations involving actors who are heterogeneous in various respects, including initial wealth, property rights, motivations, and access to different types of agency and power (Westley et al., 2013).

Seen this way, there appears to be a natural tension between a bio-economic modeler's need to simplify the diversity of operational units considered, and an institutional analyst's concern for understanding heterogeneity among units. Heterogeneity of operational units can be integrated into bio-economic models in several ways. For example, heterogeneity within a household can be integrated into a bio-economic model by allowing the model to be informed by game-theoretic depictions of interactions following cooperative or non-cooperative behaviors (Basu, 2006; Koolwal and Ray, 2002; Lancaster et al., 2006).

b) Objectives

Solutions to bio-economic optimization models depend upon the specification of an objective function or decision rule that assumes a certain type of behavior. The economics discipline tends to focus on explicit objectives of individual decision makers, such as maximization of utility from consumption or profits from production and sale of outputs, or cost minimization. Benefit-cost analysis is used to aggregate measures of individual utility across a defined group. Institutional analysts often add to actor objectives the utility of other actors and choice of institutions for horizontal and complex coordination. These could be reflected in bio-economic models through specification of the objective function.

c) Motives and Incentives

Bio-economic models often assume extrinsic (external) motives and incentives (e.g., optimization for material or monetary reward). Institutional analysts add to this consideration of intrinsic (internal) social and moral motives (e.g., sense of achievement or recognition), and they consider split intrinsic and extrinsic incentives[5]. The field of experimental economics has been applied to understanding the ways in which intrinsic motivations and extrinsic incentives interact to affect behavior. A general finding is that intrinsic motivations and extrinsic incentives are not separable. In some cases, extrinsic incentives serve to undermine or 'crowd out' intrinsic motivations, and in other cases, extrinsic incentives serve to encourage or 'crowd in' intrinsic motivations (Bowles, 2008). Several experimental economics studies have investigated motivational crowding in an environmental context (Cardenas, Stranlund and Willis, 2000). The existence of unaccounted for intrinsic motivations may cause important deviations in bio-economic models between predicted and actual behavior.

Bio-economic modelers could respond to this in several ways. They could attempt to assess the presence and magnitude of intrinsic motivations through experimental studies with the relevant population. The effects of intrinsic motivations could then be incorporated in a model through some type of adjustment factor. Another approach would be to first compare predictions from models with actual behavior; then explore intrinsic motivations that could explain deviations. Motives and incentives could be incorporated in bio-economic models through a change in specification of the objective function or constraints.

d) Decision-Making Process

In standard bio-economic models, it is assumed that operational units make decisions based on perfect information and rationality such that they maximize the net present value of a stream of expected future income. In institutional analysis, however, it is assumed that operational units make decisions based on imperfect information, informational asymmetries, and bounded or fuzzy rationality, and that they use a variety of strategies for making decisions in complex systems[6] (Cardenas and Ostrom, 2004; Heckbert, 2009).

[5] A growing number of economists, including institutional economists, are following the lead of psychologists in giving greater consideration to motives other than the maximization of consumption and profits, variously called moral sentiments by Adam Smith in 1776, moral behavior by Bowles (2008), and intrinsic motivations by many others. As stated by Bowles (2008, p.1605), "people act not only to acquire economic goods and services but also to constitute themselves as dignified, autonomous, and moral individuals".

[6] Cardenas and Ostrom (2004) provide evidence using experimental economics to support the hypothesis that individuals' decision-making in collective action situations is greatly affected by the way that they learn and

3.4.5 Interactions

The interactional considerations of bio-economic models are usually restricted to interactions between sub-units of the eco-system, or between the eco-system and production units. Issues tend to be about boundary sharing, geographic proximity, and between-unit travel costs. (These are depicted by the diagonal arrows in Figure 2.) Hydrologic models, such as the Soil and Water Assessment Tool (SWAT), depict flows of water and sediment (Jayakrishnan et al., 2005), while epidemiological and entomological models depict flows of fungi or insects across agricultural landscapes (Plantegenest et al., 2007). Economic interactions, for accessing inputs and converting outputs into benefit streams, are guided by the market based on price information. This restriction is sometimes relaxed in bio-economic models that seek to model some market imperfections. In addition to these considerations, institutional analysis emphasizes the institutional underpinnings of market interactions that define the costs of transactions, such as property rights, laws and regulations, as well as the market imperfections that might exist and necessitate actors to interact outside of formal markets.

There are at least two general possibilities for capturing inter-actor interactions in bio-economic models: (1) game-theoretic depictions of interactions among different types of agents, following cooperative or non-cooperative behaviors (Cardenas and Ostrom, 2004; McCarthy et al., 2003; Narloch et al., 2012; Rustai et al., 2010); and (2) agent-based models, in which each agent has its own motives and decision rules, and there is an aggregation process for summing across agents (Epstein, 2006; Heckbert, 2009).

The focus in institutional analysis is on the ways that different types of policies, governance groups, networks, and, especially, institutions structure those interactions (Ostrom, 2007; Ostrom and Cox, 2010). There are several ways to characterize institutions. Williamson (2000) characterizes a hierarchy of four levels of institutional conditions within which agents and groups operate: (1) the broad socio-cultural traditions and norms within which specific institutions are embedded (e.g., Anglo-Saxon law); (2) the institutional environment of rules, conventions and rights (e.g., property rights); (3) the governance environment of networks, groups, organizations, and public agencies that implement institutions (e.g., the degree of decentralization); and (4) the marginal conditions that effect individual behavior (e.g., taxes, subsidies, fines, and fees).

Institutions can also be characterized by function. For cases involving agriculture and natural resource management, the focus tends to be on three functions: property rights, exchange, and collective action. Property rights institutions define the rights, duties, and privileges of agents to access, withdraw from, manage, exclude others' use, and alienate flows of products and services

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interpret information about: the material incentives of a specific production function, the dynamics of the game, the composition of the group, and the individual characteristics of the players.

emanating from the natural environment (Agrawal and Ostrom, post-1999). Exchange institutions facilitate the flow of goods and services among producers, intermediaries, and consumers. Collective action and other coordination institutions are "formed by groups of people in order to overcome certain common problems over an extended period of time by setting certain rules regarding access to the group (membership), use of the resources and services the group owns collectively, and management of these resources and services" (Institutions for Collective Action, 2013).

Figure 5 is the "CAPRi Box" that is used by the Collective Action and Property Rights (CAPRi) program to depict the biophysical-technical imperatives of agricultural technologies and natural resource management approaches for institutions in terms of the need for tenure of secure property rights and coordination of actor interaction (Knox et al., 2002). As in Figure 2, the horizontal axis depicts the temporal scale or cycle length of the technology or management practice, while the vertical axis depicts its spatial scale. The longer the time duration or cycle length, the more important is security of tenure over rights to resources; the larger the spatial extent, the more likely the involvement of inter-agent interactions and the importance of coordination of actors' behavior. The need for tenure security and coordination of different technologies is represented by their location on the plane bounded by the x and y axes. For example, a yearly rental contract may provide sufficient security of tenure of rights to incent a farmer to adopt a high-yielding variety of an annual crop, because all of the yield benefits are returned within that year, while long-term tenure security may be necessary for a farmer to plant slow-growing mahogany trees.

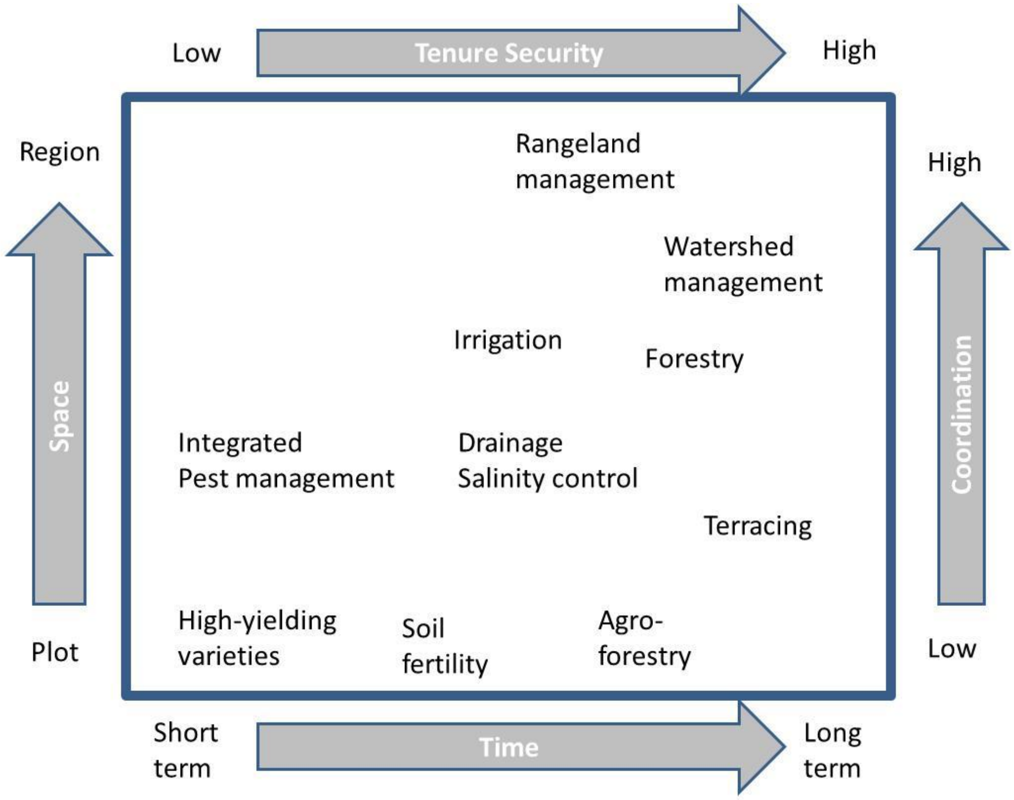

Figure 5 Biophysical-technical imperatives for institutions in agriculture and natural resource management (Source: Knox et al., 2002)

Consideration of Figure 2 and Figure 5 together can spotlight several relationships between scale and interactional issues. First, Figure 5 illustrates the difficult decisions that model builders need to make regarding spatial boundaries and temporal relations, and their implications for interactions. For example, some agroforestry systems reach a mature state after 3-4 years (e.g., fallows of *Tephrosia vogelii* or *Gliricidia sepium*), while others reach maturity only after 30-50 years (e.g., mahogany, *Swietenia macrophylla*). Second, Figure 5 clarifies the governance and institutional complexity that is entailed in bio-economic models of large-scale, long-duration management issues, such as watershed and rangeland management. Finally, the placement of a natural resource management issue on the plane between the horizontal and vertical axes depicted on Figure 5 provides some insight into the aggregation issues that likely need to be addressed in bio-economic models that address that issue.

3.4.6 Outcomes

The outcomes of concern for bio-economic models are production outputs, changes in natural capital, consumption, and profit. In addition to these, institutional analysis adds equity issues and latent demand for institutional change.

3.4.7 Scales and Aggregation

The scale issues in bio-economic models include spatial scale, boundaries, and temporal scale/cycle length.

a) Scale Issues

i. Spatial Scale

In bio-economic models, spatial scale is defined by matching the spatial scales of biophysical-technical processes with those of operational or decision-making units. Institutional analysis augments this by matching the biophysical-technical and operational scales with the social and administrative governance scales. Bio-economic models often assume homogeneity or insignificance of the size of the production unit, whereas institutional analysis often looks at the impact of size of the operational unit on transaction costs--information, contract negotiation, and contract enforcement--that might affect, for example, access to input and output markets and differentials in farm-gate and market prices, as well as the transaction costs of governance. Other aspects of economies of scale that represent the benefits of collective action are also analyzed.

ii. Boundaries

There is a need to define the boundary of the bio-economic system being modeled in terms of the biophysical definition of the natural resource, and match this with both units of economic significance such as decision-making units, markets, and fixed or fuzzy social and administrative boundaries. As stated above, one of the key challenges of bio-economic modeling is often the distinct tension between boundaries that are defined in biophysical terms and those that are defined in social-institutional terms. For example, the boundaries of river basin catchment areas--areas of land that drain to single outlets into a larger river, lake or ocean--rarely coincide with the boundaries of administrative areas. Indeed, rivers are often chosen to be the boundaries between administrative areas. Inability to deal with water resource management challenges may end up being the source of lingering tensions between geographic neighbors, as is the case for the Nile River basin in East Africa. Alternatively, concerns about other topics of mutual interest may serve as barriers to effective collective action across boundaries (Swallow, Johnson and Meinzen-Dick, 2002; Swallow, van Noordwijk and Garrity, 2002).

iii. Temporal Scale and Cycle Length

Certain aspects of ecological and biophysical-technical processes are in a constant state of flux. The same can be said of institutions, in the sense that actors are constantly updating, reaffirming or questioning, their expectations of others' behavior. And, both systems have break-points or thresholds of tolerance for the *status quo* before a new order asserts itself.

Although there are some aspects of variation, biophysical-technical production processes tend to have relatively certain cycle lengths (Whitten and Bennett, post 2004). For example, annual crops have specific time periods from planting to harvest, while livestock and aquatic systems have specific periods of breeding, growth and maturation. Farmers' investment decisions related to these processes must be matched to these cycle lengths. For example, a Sahelian farmer growing crops without irrigation has fairly short windows of opportunity to make decisions about planting material, plant density, fertilizer composition and application rate, pesticide dosage and timing, and harvest date. Indeed, it is often the certainty around the cycle lengths of these systems that give bio-economic models their structure and allow for some level of certainty in their predictions of cause and effect.

Some of the important institutional issues that affect and are affected by biophysical-technical processes can be reasonably modeled on the same time scale. For example, decisions about floor or ceiling prices must be matched with crop production cycles. These are issues that arise at Williamson's (2000) fourth level of institutional conditions–-marginal conditions. However, higher level institutions related to governance or institutional structures are unlikely to change in accordance with a particular biophysical-technical cycle. In a democracy, for example, the four or five-year cycle of elections may be more important for institutional change than single-year crop, livestock or aquaculture production cycles. An additional aspect of institutional change is that the paths through a single cycle and cycle lengths are not as predictable as they are for biophysical-technical processes and therefore their related economic cycles.

b) Aggregation

As indicated above and in Figure 1, bio-economic modeling often involves procedures for aggregating the outcomes of actor behavior from smaller to larger spatial and temporal scales. The complexity of the aggregation process depends upon the particular process and available data. For example, Ewert et al. (2011) describe the aggregation from plot to farm as involving four related elements: (1) aggregation into types of crops and rotations; (2) spatial aggregation/averaging of crop rotation outputs and temporal aggregation of annual outputs to mean and standard deviation of a multi-year period; (3) disaggregation of crop management from sub-region to farming system; and (4) derivation of technical coefficients from model input and output relations. Biophysical-technical processes can be aggregated either linearly or non-linearly—with break-points or thresholds; neo-classical market processes are aggregated linearly. In institutional analysis, scale issues are significant and highly varied, often being depicted non-linearly.

3.4.7 Sources of Variation, Risk and Uncertainty

In bio-economic systems, sources of variation, risk and uncertainty arise from both endogenous and exogenous sources. Endogenous sources include those arising from the biophysical-technical production side, as well as those arising from the economic side, which include, for example, human capital (e.g., human health) and prices for inputs and certain outputs. Exogenous sources include exogenous influences and stochastic disturbances that affect the state of the natural resource, the operational unit(s)' decision context, and production and marketing activities, but are not affected by those activities (e.g., climate, weather, pests and diseases, and global economic downturn that affects global market prices for inputs and certain outputs). In order to analyze policy impacts, some bio-economic models incorporate changes in policy as a source of exogenous variation.

In institutional analysis, these same sources of variation, risk and uncertainty are analyzed; however, institutional analysis includes the impact of exogenous factors on institutions. And, whereas bio-economic models based on the neo-classical economic model assume that governance, policy, and institutions are fixed and therefore not responsive to the outcomes of the processes depicted, institutional analysis assumes that at least some aspects of the institutional context are responsive to the actions of operational units. For example, institutional analysis looks at situations where there is information scarcity, informational asymmetry, and a failure of the insurance market, such that the focus is on identifying operational units' strategies to mitigate risk, including the use of non-market transactions and efforts to established risk-mitigating norms. Conversely, institutional analysis also assumes that the choices of operational units and thus outcomes are impacted by the costs of institutional change for both individuals and governance groups.

Therefore, one of the main challenges of integrating institutions into bio-economic models is distinguishing between the elements of the institutional context that can be assumed to be fixed, and the elements that can be considered to be dynamic within the scope of a particular model. Williamson (2000) considers four institutional levels as shown in Figure 4: socio-cultural norms and traditions, institutional context, governance context, and marginal conditions. It will generally be appropriate to assume that the processes depicted in a bio-economic model of sustainable intensification will have no effect on socio-cultural norms and traditions, may or may not have limited effect on the institutional context, may have some effect on the governance context, and will likely have some effect on marginal conditions.

3.4.8 Impact Pathways and Externalities

Impact pathways trace the linkages between outcomes and the well-being of those directly or indirectly involved in the bio-economic system depicted by a model. Of specific importance are the positive or negative externalities for those outside of the system *per se* (e.g., changes in the quality of water available to downstream water users). In bio-economic models based on the neo-classical economic model, impacts are outputs and physical externalities as well as prices and the value of externalities. In addition to these, institutional analysis looks at the ways in which institutions can effect, and be effected by, these impact pathways. The realization of externalities can result in demand for institutional change to readdress the situation.

A private property rights context provides high degrees of discretion over production decisions, but can allow more externality costs than other types of rights contexts. Institutional arrangements for dealing with environmental externalities in the context private rights include regulatory mechanisms (e.g., zoning and quotas), market (dis-)incentives mechanisms (e.g., taxes, permits, subsidies, and payments), and facilitated-voluntarism mechanisms (e.g., informational campaigns and extension) (Swallow et al., 2009). Village-level common property regimes, on the other hand, may lead to less efficient resource use, but they internalize costs within the village.

3.4.9 Feedbacks and Learning

Just as in standard bio-economic models, feedbacks or updating mechanisms are central to institutional analysis. However, institutional analysis incorporates feedbacks not only from natural resource management, production, and marketing, but also from non-market interactions regarding those activities as well as interactions over institutional and policy choice itself. This is depicted in Figure 4 by the dashed arrows from the Interactions box to the Action Situations box and from the Outcomes box to the Action Situations box and the joined Biophysical-Technical and Institutional Conditions boxes. Also, in institutional analysis user learning and adaptive decision-making in response to interactions and outcomes are central.

In bio-economic models based on the perfect market model, feedbacks occur in the form of changes in supply and demand that are communicated through changes in market prices. In institutional analysis, feedbacks occur in the form of changes, for example, in: absolute scarcity of or demand for resources or other forms of productive capital (which can induce demand for institutional change); demand for new infrastructure or technologies (and possibly demand for accompanying institutions); demand for new forms of property rights; demand for new levels of information provision (grading and certification), monitoring, and enforcement of rules or property rights; demand for new forms of market exchange; or demand for new forms of collective action or governance (Hagadorn, 2008; Westley et al., 2013).

In bio-economic models, feedbacks depend on cycle lengths and buffers, and can be modeled as static or dynamic (recursive, inter-temporal, dynamic recursive, or stochastic). In institutional analysis, the focal feedbacks are socio-economic and depend on transaction costs, informational asymmetries, agency, and political power. In bio-economic models, the process of change itself is typically not considered to be costly, whereas in institutional analysis it involves real and transaction costs for both the individuals and the governance groups involved. In both the biophysical-technical side of bio-economic models and in institutional analysis, there are break-points and thresholds—degrees of irreversibility of environmental impact and build-up of latent demand for institutional change--after which the current *status quo* is no longer tenable and must be changed to maintain resilience of the system (Hagedorn, 2008, 2012; Ostrom and Cox 2010; Westley et al., 2013; Whitten and Bennett, post 2004).

Table 1 Matching the Key Elements of Bio-Economic Models and Institutional Analysis

Table 1 Matching the Key Elements of Bio-Economic Models and Institutional Analysis

Key Elements of Bio-Economic Models	Bio-Economic Models		Incorporating Institutions
	Biophysical-Technical	Economic (Perfect Markets, Costless Transactions)	Socio-Economic (Imperfect Markets, Costly Transactions, Endogenous Institutional Change)
Resources/Capitals	Eco-systems/natural	+Physical, financial & human	+Social, institutional & political
Activities			
Activities	Production	+Capital allocation & marketing	+Transactions; institutional & policy change
Dynamic Processes	Recursive, dynamic recursive,continuous, dynamic stochastic	+Marginal intensity & enterprise/tech. change	+Response to needs; fixed transaction costs of institutional change
Constraints	Endowments Technical feasibility	+Prices*	+Norms; laws; regulations; taxes/subsidies
Operational Units	Production unit	+Unitary, homogeneous actors	Integrated households; heterogeneous actors
Objectives	Production	+Utility: profit, consumption, costs	+Horizontal & complex coordination
Motives / Incentives	---	Optimization, extrinsic incentives	+Moral & social motives; split incentives
DecisionMaking Process	---	Perfect information & rationality	Imperfect information & fuzzy rationality
Interactions	Biophysical-technical	+Markets*	+Defined by institutions; governance units enforce
Outcomes	Production outputs +/- Natural capital	+Consumption +Profit	+Demand for institutional change
Scales etc.			
Spatial Scale	Biophysical-tech. definition	+Matchw/decision-making unit	+Match w/administrative & social scales
Boundaries	Resource/ecosystem /watershed	+Match w/decision -mak'g units&mrkt	+Match w/fixed/fuzzy social & administrative boundaries
Temporal Scale	Biophysical-tech. cycles & thresholds	+Investment-&-return cycle	+Institutional/policy change cycles, & thresholds
Aggregation	Linear or non-linear	+Market, linear	+Non-linear
Exogenous & Stochastic Events	Biophysical-technical	+Prices*	+Higher scale institutions +Some institutions w/o scale
ImpactPathways& Externalities	Outputs; physical externalities	+Prices, value of externalities	+Demand for institutional change
Feedbacks & Learning	Natural capital stock changes	+Prices/marginal conditions change	+Institutional & policy change

4) Examples of Bio-Economic Models in which Different Types of Institutions are Explicitly Depicted

Bio-economic models are built employing either one of the different types of full, complex system models or an integrated framework of several of these models as sub-systems. Some of the full, complex system models that have been used are: standard optimization, Bayesian network, systems dynamics, evolutionary, and agent-based models[7] (Brown, 2000; Heckbert et al., 2010; Janssen and van Ittersum, 2007a; Prellezo et al., 2010; Upadhyay et al., 2006). In integrated frameworks, either a single model--such as a Bayesian network, systems dynamics, or an agent-based model--is used as a linking model, or outputs from compatible sub-system models are used as inputs into others in a hierarchical manner.

To inform choice of model, internal structure, variables, and parameter values for these models, bio-economic modelers often use empirical regression analysis. Bio-economic modelers who seek to explicitly integrate institutions in their models may, in addition, use concepts from game theory or experimental economics. For example, laboratory experiments can be designed as games that generate game-theoretic data (Cavalcanti et al., 2013). Although game-theoretic depictions of non-unitary household models have been developed, they await integration into bio-economic models. Table 2 summarizes some of the ways in which institutions have been integrated into these various types of bio-economic models, as well as the models' pros and cons, and applicability vis-à-vis bio-economic institutional analysis for sustainable intensification in developing countries.

In the remainder of this section, some of the ways in which modelers have explicitly integrated institutions into economic and/or bio-economic models are illustrated through twelve extended examples that were selected to represent the range of diversity of approaches and perspectives. With respect to sustainable intensification in developing countries, the examples were selected in an attempt to touch on or fully encompass the relevant range of types of: resource spatial scales (intensive and extensive); resource types (croplands, rangelands, coastal waters, catchments, wetlands, and forests); production system types (crops, trees, livestock, and

[7] All model types discussed here have been used to model ecological, agricultural, and social systems. Each has pros and cons that condition their applicability for and their means of depicting institutions and policy. Although not discussed here, conceptual and empirical regression models are also useful for understanding the role of institutions in sustainable intensification for development. Conceptual models are used as the first step in all types of model building, and they are especially instrumental in facilitating the type of interdisciplinary discourse for building models that would be required for bio-economic models in which institutions are explicitly integrated (Herrmann et al., 2012). Empirical models, which employ regression techniques and factor analysis, are useful for describing the aggregate characteristics and revealing previously unknown inter-relationships of complex systems, as well as parameterization and evaluation of other model types. And, conversely, empirical regression models depend on other model types to determine appropriate variables, instrumentation, structure, analysis, and interpretation. But, empirical regression models have limited applicability as bio-economic models because they lack the ability to analyze actor interactions or system dynamics (Heckbert et al., 2010).

aquaculture/fisheries); governance groups (households (unitary and non-unitary), networks, and collectives (common property), and nations (markets)); institution-related problematic areas (the distribution of endowments, property rights, missing markets, and externalities); policy options in terms of investment target (conservation and biodiversity, infrastructure and technology, equity, land reform, governance, social safety nets, and jump-starting input markets); policy instruments (regulatory, market (dis-)incentive based, and facilitated-voluntarism); scales of economic analysis (micro- and macro-economic); and economic and bio-economic model types (standard optimization, Bayesian network, systems dynamics, evolutionary, and agent-based).

The twelve extended examples include:
(1) a game-theoretic bargaining model of intra-household interactions, applied to the targeting of micro-credit in Bangladesh (Ngo and Wahhaj, 2012);
(2) a game-theory informed empirical model of non-rule based cooperation in risky environments, applied to common-pool rangeland management in semi-arid Ethiopia (McCarthy et al., 2003);
(3) a dynamic game-theoretic model of payments for environmental services (PES) for agrobiodiversity, applied to the choice of individual versus group payments for quinoa production in the Peruvian and Bolivian Andes (Narloch et al., 2012);
(4) an evolutionary model of the social networks of an entire economy used to study technological innovation and ultimately macro-economic growth, applied globally (Fogli and Veldkamp, 2013);
(5) an endogenous network formation model explored using non-cooperative game theory and numerical simulations, applied to understanding the effects of targeted social safety-net transfers on networks, and thus technique adoption, economic mobility, and poverty traps (Chantarat and Barrett, 2012);
(6) a stochastic dynamic programming optimization model of technique adoption, applied to analyzing the impact of a short-term water market on the pathway of investment in water-conserving irrigation technologies in the Central Valley of California (Carey and Zilberman, 2002);
(7) an agent-based, full bio-economic system model, applied to ex ante assessment of the use of a cap-and-trade system for fertilizer pollution permits to manage water quality in the coastal wetlands that feed into Australia's Great Barrier Reef World Heritage Area (Heckbert, 2011);
(8) a discrete-time, dynamic model of co-management, applied to African rangelands (Swallow and Bromley, 1994);
(9) a discrete-time, dynamic model of land and forest use, applied to rural Indonesia (Fernandez, 2006);
(10) an integrated full bio-economic system systems dynamics model, applied to the improvement of common-pool freshwater use for crop irrigation, riverine tourism, and oyster production in coastal France (Mongruel et al., 2011);

(11) a seven-model, full bio-economic system integrated framework, applied to the case of ex ante assessment of the implementation of the EU nitrate scaling-up directive in the Midi-Pyrenees of France (van Ittersum, 2009); and
(12) a model of policy threshold analysis using a full bio-economic system Bayesian network model, applied to ex ante identification of the 'best bet' policy instrument for the management of private wetlands in Australia (Whitten and Bennett, post 2004).

4.1 Calibrating Actor Decision-Making

Bio-economic modelers have used several different approaches to calibrate the decision-making processes of actors. The most basic approach is to follow the conventional assumptions of perfect information, rationality and utility maximization. As described above, many situations of relevance for bio-economic modeling of sustainable intensification in developing countries deviate considerably from these characteristics. To provide alternatives to these restrictive assumptions, and to capture more of the complexity in bio-economic systems, modelers have typically calibrated decision-making using empirical data from surveys and interviews (Janssen and Ostrom, 2006). However, since surveys and interviews are only conducted at one point in time, this method does not do well in capturing dynamic situations like sustainable intensification. Two remedies are to use participatory modeling with stakeholders, or experimental economics methods where individuals reveal dynamic decision-making strategies through role-playing games in well-defined circumstances (Heckbert, 2009).

4.2. Depicting Interactions

Most bio-economic models assume an individual or unitary household as the decision-making unit. For situations in which this is not the case, collective models of decision-making are needed. Some work has been done using game-theoretic models to depict collective decision-making processes within the household. Although use of these models is recent and they have yet to be integrated into bio-economic models, such efforts are essential first steps in this process. And, some work has been done using game-theoretic models to depict decision-making within collectives that manage common-pool resources (Cardenas and Ostrom, 2004; Himmelweit et al., 2013; Narloch et al., 2012; McCarthy et al., 2003; Rustai et al., 2010; Swallow and Bromley, 1994). Collectives have also been modeled using agent-based full bio-economic models (Epstein, 2006; Heckbert et al., 2010). Market interactions have been modeled using Bayesian network models (Kragt et al., 2010; Whitten and Bennett, post 2004) and agent-based models (Epstein, 2006; Heckbert, 2009).

4.2.1 Depictions of Interactions in Non-Unitary Households: Game Theory and a Standard Optimization Model

Concern for a better understanding of interactions within households arose out of empirical observations that the theory of the unitary household model often guided policy choices that did not elicit the expected household responses and outcomes, or even inadvertently reduced the welfare and bargaining power of some members of households, usually women. This is important for intrinsic reasons. But, it is also important for the efficacy of development and sustainability policy. There is considerable empirical evidence that women have relatively strong preferences for household public goods, such as nutrition, health and education, and they have productive potential that is constrained by capital[8]. Some examples of specific areas of policy analysis that have been investigated using non-unitary household models are beneficiary targeting for programs delivering social safety net benefits, microcredit, and extension for nutrition and health, enterprise and technique adoption, and commercialization of value chains (Ngo and Wahhaj, 2012).

Although the concept of the unitary household and its use in economic models persists, largely due to ease of empirical application, by the mid-1990s, the burden of proof for justification of model choice shifted from use of the non-unitary to the unitary model (Doss, 2011; Fuji and Ishikawa, 2013; Haddad et al., 1997; Himmelweit et al., 2013). That is, unless there is evidence to the contrary, it should be assumed that the actors within a household are heterogeneous (in power, endowments of capital and domains of control, objectives, preferences, enterprises, techniques, and constraints[9]); the intra-household distribution of power affects allocations of capital and domains of control, and ultimately outcomes; and decision-making processes do not necessarily arrive at Pareto-efficient[10] outcomes (Doss, 2011).

The two most influential types of non-unitary household models are game-theoretic depictions of bargaining interactions: (1) Pareto-efficiency assuming, cooperative (collective) bargaining

[8] Although theoretical and empirical development in the field of intra-household decision-making has been hindered in part by the lack of appropriate and comparable data, it is hoped that this situation will be alleviated by the development and systematic publication of a newly developed Women's Empowerment in Agriculture Index (WEAI) which measures women's empowerment using two sub-indexes: the percentage of women who are empowered in five domains (decisions about agricultural production, access to and decision-making power about productive resources, control of use of income, leadership in the community, and time allocation) and a Gender Parity Index that reflects the percentage of women who are empowered or whose achievements are at least as high as men in their households. Use of WEAI has been piloted in projects in three countries: Uganda, Guatemala, and Bangladesh (Alkire et al., 2012).

[9] In much of Africa, for example, wives and husbands cultivate separate plots (often with scale and fertility differentials), and there are often gender-specific crops, tasks, priorities for peak-season labor and capital allocations, techniques, market participation, output distributions, and responsibilities for household care tasks. These gendered aspects have strong implications for outcomes in terms of both efficiency and equity, as well as food security, resilience and sustainability (Dulfo and Udry, 2004).

[10] In the sense that no single individual in the household can be made better off without making another worse off (Doss, 2011).

models[11]; and (2) non-Pareto-efficiency assuming, non-cooperative bargaining models with threat-points of non-cooperation or exit/divorce (Himmelweit et al., 2013; Xu, 2007). Cooperative models include cooperative bargaining models and dynamic cooperative bargaining models (Ligon, 2002). Several cooperative models have been constructed in which the balance of bargaining power is endogenously determined (Basu, 2006; Koolwal and Ray, 2002; Lancaster et al., 2006).

Use of these non-unitary household models has paved the way for conceptual understandings with strong implications for institutional and policy analysis. Studies have shown the importance of common and individual plots within a household (Kazianga and Wahhaj, 2013), gender-differentiated production tasks and spheres of joint and independent control (Basu, 2006; Ngo and Wahhaj, 2012), public and private consumption goods (Dulfo and Udry, 2004; Fuji and Ishikawa, 2013; Ngo and Wahhaj, 2012), non-separability of production and consumption decisions (Fuji and Ishikawa, 2013; Ligon, 2009), impacts of the distribution of bargaining power on intra-household resource allocations and outcomes (Dulfo and Udry, 2004; Fuji and Ishikawa, 2013), the possibility of unequal independence of decision-making and sharing of credit (Ngo and Wahhaj, 2012), and the possibility of unequal exposure to and lack of pooling of idiosyncratic risks across gender differentiated enterprises (Dulfo and Udry, 2004; Lignon, 2009).

Ngo and Wahhaj (2012) offer a dynamic bargaining model with a Cournot-Nash Pareto-efficient equilibrium in which there are independent and joint production enterprises, a strict gender-differentiation and asset specificity of production tasks, access to micro-finance, private and public consumption goods, and the threat of non-cooperation or divorce. The context is that of a highly patriarchal society, such as exists in Bangladesh, in which cultural norms place strong restrictions on appropriate production tasks for married women, and public goods and income are divided into separate spheres of control. Loan specifications are that both spouses are responsible for repayment of a portion of a loan, and, in the case of non-cooperation, husbands hold rights to veto or appropriate loans.

This model shows that participation in micro-credit programs can either increase or decrease a woman's bargaining power within the household depending on: the choice of activity in which the loan is invested (independent or joint), and the initial conditions of the distribution of both bargaining power and relative individual preferences for private or public goods. A woman's

[11] Collective models often specify a household utility function as a weighted sum of individual utilities where weights can be interpreted as reflecting an individual's bargaining power. Outcomes can affect these weights, such that weights should be estimated simultaneously with outcomes. Empirical data can be analyzed to identify the impact of exogenous factors on these weights, and ultimately outcomes. Such exogenous factors might include those that can be impacted by policy such as the development of gender friendly labor and other markets, human capital (education, skill training, nutrition, health and laws against gender-based violence) and social capital (network development). Empirical data can also be analyzed to identify the impact of the weights on outcomes such as the intra-household distribution of capital (including income sharing and risk-mitigation strategies), relative productivity of the various household enterprises, and budget shares (Doss, 2011; Koolwal and Ray, 2002).

bargaining power is more likely to increase when credit is invested profitably in a joint production activity or when a large share of the household budget is devoted to household public goods. In this case, acceptance of credit shifts the intra-household bargaining power towards greater equality, and the shift is small enough that it does not threaten the dominant member's position enough to trigger the defensive move of exercising the right to veto or appropriate the loan.

Central to this finding is the impact of the loan, which in the case of investment in a joint production activity is only an 'income effect', but in the case of investment in an independent activity includes a potentially countervailing non-cooperative 'threat-point effect' which depends on the initial distribution of bargaining power and relative preferences for private and public goods. The 'threat-point effect' favors the member in the stronger bargaining position and the member with the lower preference for pubic goods. These two impacts of a loan on an independent production activity mean that the overall impact is ambiguous. And, the potential threat to bargaining positions means that spouses would not necessarily prefer an efficient choice. The choice to invest the loan in a joint activity is more likely if efficiency is higher in that activity than in an independent activity, and an increase in women's bargaining power is more likely if women are skilled in that joint activity. Thus, a micro-credit program may want to promote use of credit for a joint activity in conjunction with efforts to increase both the efficiency of and women's skills in that activity.

4.2.2 Depictions of Interactions in Collectives: Game Theory, an Empirical Regression Model, and a Standard Optimization Model

Two potential functions of collective groups are to coordinate the use of common-pool resources such that crowding and overexploitation is avoided, and to achieve economies of scale, such as those needed to form vertical linkages to access legal rights, extension, or marketing opportunities. Collective decision-making is particularly problematic in situations where the transaction costs of collective decision-making are high, such as when there is inadequate information[12] or heterogeneity (conflict) of interests, or due to the characteristics of the transaction good/service or its ecosystem of origin.

These situations present social dilemmas that can be modeled as games. Assurance games are used to model situations in which individuals' lack of information prevents coordination despite common goals. "Battle of the sexes" games are used to model situations in which the heterogeneity of goals prevents cooperation. "Chicken games" are used to model situations in

[12] Cardenas and Ostrom (2004) provide evidence using experimental economics to support the hypothesis that individuals' decision-making in collective-action situations is greatly affected by the way that they learn and interpret information about: the material incentives of a specific production function, the dynamics of the game, the composition of the group, and the individual characteristics of the players.

which heterogeneity of expected benefits prevents cooperation. And, "social dilemma" (common-pool resource) games are used to model situations in which the rivalry of consumption and difficulty of exclusion make provision and sustenance of common-pool goods particularly challenging (Poteete and Ostrom, 2004). Collectives can use institutions to overcome these social dilemmas. For example, collectives can balance out individual motivations of self-interest by strengthening social norms such as altruism and reciprocity (unconditional and conditional cooperation), fairness (inequity aversion), and safety-first (risk aversion) (Narloch et al., 2012).

McCarthy et al. (2003) provide a game-theory informed empirical regression model of non-rule based cooperation in risky environments applied to common-pool rangeland management in semi-arid Ethiopia. They used a standard non-cooperative game to parameterize the stocking density on common grazing areas such that overgrazing increased with the number of households. Hypotheses were tested about the effects of increased rainfall variability, arising for example from increased climate variability, on the community's capacity to co-operate, and ultimately sustain intensified resource use in terms of stock densities and land allocation patterns (land for common pasture, private pasture, and crops). Consideration was given to the impact of group members' use of common pastures located outside of the community and non-group members' use of community common pastures. They found that, in the case under study, cooperation reduced overexploitation of the commons, and that cooperation increased with the profitability of the related enterprise and decreased with increased heterogeneity of community wealth and use of the commons by non-members.

Narloch et al. (2012) provide an example of a dynamic game-theoretic model of payments for environmental services (PES) for agrobiodiversity of a threatened variety of a landrace crop species applied to quinoa production in the Peruvian and Bolivian Andes. Their policy question was whether PES should be provided to private individuals or a collective community. The crop is modeled as an impure public good in which there are both private and collective benefits, but only individual production costs. The social dilemma is that private payoff levels are dependent on the conservation levels of peers because, for any public benefit to arise, a threshold aggregate amount of land must be planted in the threatened variety, such that the private land allocation decision is dependent on expectations of others' choices. It is assumed that the return to the threatened variety is lower than the return to the alternative, commercial variety. The option of private PES rewards was introduced as a private conservation cost reduction, and the option of collective rewards was introduced as an increase in the public conservation benefit shared equally by all. The results showed that PES policy success was dependent on careful linkage to support local informal institutions and the choice between private and collective rewards is instrumental to this and was sensitive to market and group contexts that need to be assessed on a case-by-case basis. Swallow et al. (2002) provide a similar game-theoretic analysis of the differential success of communities in using a mixed public-private good (a pour-on insecticide) for controlling tsetse flies in Ethiopia. Rustai et al. (2010) also model conditional cooperation in the context of costly monitoring of a forest commons in Ethiopia.

4.2.3 Depictions of Interactions in Social Networks: Network Diffusion Theory, an Evolutionary Model, and a Standard Optimization Model

Like collective groups, social networks can also be instrumental in sustainable intensification. In the context of imperfect markets in developing countries, social networks are used to access a variety of types of capital, including information about technology. Like collective groups, social networks can also be instrumental in motivating pro-social behavior, such as the adoption of more environmentally friendly production techniques. However, compared to collective groups, networks are often more difficult to observe and measure, and they may require even more attention to the analytical problems of reverse causality and endogeneity (Fogli and Veldkemp, 2013).

Fogli and Veldkamp (2013) study the impact of social networks on economy-wide technological innovation by employing a variety of network diffusion models and an evolutionary model[13] to inform empirical regression analysis. Noting the similarity of the processes of disease transmission and diffusion of technological innovation through human contact via social networks, they examine the effect of the structure of social networks on the speed of technology diffusion, and ultimately an economy's macro-economic growth. Fogli and Veldkamp (2013) characterize social network structures in terms of their degree of collectivism (number of links), link stability (prevalence of link changes), and fractionalization (sub-groups with few links) [14], and then categorized them as facilitating low- or high-diffusion rates.

In their simplified evolutionary model that focused on the degree of collectivism, there were two types of individuals, individualists and collectivists, two types of technology, low and high returning, and two types of diseases, acquired or not through social contact. It was assumed that the difference in the transmission rates of the two disease types had no direct effect on the rate of technological diffusion. At birth, each individual inherited the best technology type--and the associated individual type—of their parents' social network. The results of the evolutionary model were used to choose variables and their instrumentation, and to parameterize a regression

[13] Rather than using an evolutionary model to model the impact of network structure on the macro-economic growth path of an economy, Cavalcanti and Giannitsarou (2013) used a standard model of endogenous economic growth, and analyzed network impact in terms of convergence speed, stability, and level of equality during transition and at the end point. Their focus was on the impact of the human capital accumulating function of social networks, and they applied their model to the study of the accumulation of education in Switzerland. Interestingly, Cavalcanti and Giannitsarou (2013) integrated social networks in their model as local externalities.
[14] Other aspects of network structure that have been studied are their cohesion (homogeneity of economic primitives such as preferences, endowments and technologies) (Cavalcanti and Giannitsarou, 2013) and each member's centricity where centricity is measured by degree (number of direct links to others) and closeness (closeness of linkage to all other members in the network) (Cavalcanti et al., 2013).

model which was run using data from a variety of sources for a large number of countries. Fogli and Veldkamp (2013) found empirical evidence of a significant effect of social network structure on the rate of technology diffusion, and ultimately GDP. In particular, they found that economies with high rates of communicable diseases will evolve isolated social networks--those that are stable, local and fractionalized—with low-diffusion rates that are efficient in inhibiting disease transmission, but unfortunately are also efficient in inhibiting technological diffusion[15].

Chantarat and Barrett (2012) also study the impact of networks on technology adoption, but they carry this further to implications for households' relative economic mobility, ability to escape poverty traps, and the potential for policy to impact the network formation capabilities of poor households. These modelers build a stylized two-period household optimization model of endogenous network formation for a polarized society--productive and social capital endowment poor and rich--with two technologies--cost and return low and high. They use numerical simulations to explore equilibrium outcomes in terms of technique adoption, patterns of social-network-mediated economic mobility, and household welfare.

The model's assumptions are that: social capital can be used as a substitute for absent financial markets; the benefit of each additional link to a social network is a reduced fixed cost of production; the benefits of prospective links are asymmetric; transactions in network formation are costly; and the costs of such transactions are asymmetric due to varying social distance. Link formation is modeled as a non-cooperative game. Chantarat and Barrett (2012) found that, contrary to the theory that public transfers might crowd out the formation of local social network capital, public transfers targeted to households that hold key positions in the process of network formation can in some cases catalyze the creation of new social network capital in a way that releases the hold of poverty traps: "[w]ell-targeted transfers can lift even non-recipients out of long-term poverty, while poorly targeted transfers can fail to facilitate economic mobility even for recipients" (p.327).

4.2.4 Depictions of Interactions in Markets: a Standard Optimization Model and an Agent-Based Model

Some of the models that have been used to depict interactions in markets are standard optimization and agent-based models. Standard optimization models were discussed in Section 4.2.1. Agent-based models (ABM)[16] are computational complex system models in which

[15] "More broadly, the paper's contribution is to offer a theory of the origins of social institutions, propose one way these institutions might interact with the macroeconomy, and show how to quantify and test this relationship" (Fogli and Veldkamp, 2013, p.32).
[16] Agent-based models are called individual-based models in ecology (Heckbert et al., 2010).

agents[17] are assumed to be heterogeneous and autonomous, use adaptive decision-making (incorporating learning) based on bounded information and rationality, and interact in a local space. And, there are assumed to be emergent properties and dynamic feedbacks that can evolve. ABMs have been used to model markets, such as emissions-trading markets. They have been used to model the impacts of each of the three types of policy instruments (regulatory, market-based, and facilitated-voluntarism). ABMs have also been used to model common-pool resource use, and the equity implications of policy (Heckbert et al., 2011; Heckbert, 2009). Epstein (2006) shows that ABMs can be used to study the way in which the rules of individual behavior can give rise in a bottom-up fashion to collective behavioral expectations, institutions and organizations. Finally, ABMs are starting to be used as links in integrated modeling systems where both the ecological and economic sides of the system are detailed and dynamic. One disadvantage of agent-based models is that there are no particular theoretical underpinnings to calibrate or evaluate models, such that it is left to individual analysts to decide how to assign decision rules for agents (Heckbert et al., 2010).

Carey and Zilberman (2002)[18] provide an example of a stochastic dynamic programming optimization model to study the private choice to change irrigation technique by investing in modern water-conserving irrigation technology when supplies of water are uncertain and there is a market for the short-term re-allocation of water among irrigation farmers who have secure but untradeable long-term water rights. The price at which a farmer can buy water is assumed to be fixed for a particular time period, but variable over time in response to changes in the uncertain supply of water which fluctuates stochastically due to changes in weather and public policy. A farmer's initial water allocation is also assumed to be stochastic. Using option value theory, Carey and Zilberman (2002) demonstrated that the existence of a water market provided farmers with the option to delay the quasi-irreversible change in irrigation technique until after observing whether water prices increased or decreased.

Carey and Zilberman (2002) used this model to analyze the pathway of investment in new irrigation technologies in the Central Valley of California. They found that rather than adopting a new technology along the lines predicted by traditional net present value theory--such that adoption would occur when the expected present value equals the cost of the investment--in situations of uncertainty and irreversibility where there is an option to delay investment, technique adoption tended to follow the option value investment rule--such that it was delayed until a stochastic event, such as a drought, vastly increased the wedge between the costs and benefits of making the change such that the expected present value exceeds the costs by a

[17] Although agents in ABMs are often individuals, it is possible for the agent in an agent-based model to be a collective (Epstein, 2006).

[18] Others have used variants of this modeling approach to examine the effects of irrigation water trading and technology choice in other contexts (Dridi and Khanna, 2005).

potentially large hurdle rate. Such an option to delay investment can be provided by a water market. They note that this finding implies a case contrary to that suggested by the standard theory that the introduction of markets tends to uniformly facilitate technique adoption. For farmers with scarce and uncertain water supplies, the introduction of a water market can provide an option to delay the fixed cost of irrigation technique adoption by relying in the purchase of water on a marginal basis.

Heckbert et al. (2011) provide an example of an agent-based model for ex ante assessment of the use of a cap-and-trade system for fertilizer pollution permits to manage water quality in an intensifying--sugar cane to residential-and-horticulture--wetlands area in coastal Australia that feeds into the Great Barrier Reef World Heritage Area. Using this model, it was determined that the small number of agents and low heterogeneity of production constituted too "thin" a market for the tool that favored a heterogeneous population, such that the transaction costs for individuals and the government would be too high to warrant establishing the system at the time. Use of the model provided several additional insights. It was found that the market-based cap-and-trade instrument would have been more effective in adapting to situations of transition than a regulatory mechanism, such as a uniform standard fertilizer application rate, which might have hindered the transition to the state of higher sustainable intensification. Also, it was found that "the internal dynamics of the regulated industry (in our case diversification patterns to higher value and higher input crops) are critical to whether inequality is increased or lessened by the emissions trading scheme" (Heckbert, 2011, p.149).

4.3 Depicting Property Rights: Game Theory and Two Standard Optimization Models

Property rights are among the most important and most heavily studied institutions affecting resource management. The concept that incomplete property rights is likely to lead to reduced investment incentive can be traced as far back as Alfred Marshall (1890). Bio-economic models can be used to depict the effects of different types of property rights on resource allocation and outcomes. On the other hand, bio-economic models can also be used to depict the demand that individuals and groups have for changes in property rights institutions as outcomes of collective choice (Demsetz, 1967).

Several bio-economic models have been used to explore the impact of property rights on resource use, in which theoretical models of strategic interactions over resource use (usually game-theoretic) are used as the basis for the structure and operation of a simulation model. For example, Swallow and Bromley (1994) explore a theoretical result from the work of Hirshleifer and Rasmusen (1989) regarding the theoretical impacts of ostracism on cooperation in a prisoner's dilemma context. Swallow and Bromley (1994) present a discrete-time, dynamic model that shows that African rangelands can be used and managed sustainability and profitably under a co-management regime in which the government effectively defends the rights of a specific set of group members, and an implicit contract is maintained among group members through members' observation and response to each other's behavior. An empirical version of the model shows the conditions under which this arrangement may replicate the private property solution. Because there is no collective per se, this approach assumes that all costs are born by individual resource users and some type of government entity that restricts access to a defined group of users. Extensions to this type of model take into consideration that monitoring others' behavior is costly (Rustai et al., 2010).

Similarly, Fernandez (2006) develops a dynamic model to explore the theoretical insights of Larson and Bromley (1990) that common property and private property may provide similar incentives for soil quality preservation. Fernandez (2006) models land and forest use in rural Indonesia. Her model includes a forest biomass function, a soil fertility function, a utility function, and a crop production function, with crop production dependent on soil fertility and farming intensity. It is assumed that production and consumption are non-separable due to an imperfect rural labor market. The farmer makes decisions to allocate land and labor between crop cultivation, fallowing and forest use. Feedbacks occur through changes in soil fertility and forest biomass. Property rights are captured through the terminal value of the natural resource--soil fertility and forest biomass. Under private property, the decision maker captures the terminal value through potential sale or bequest; under common property, the terminal value can be zero or a share of the value of the bequest to all who share the resource. The empirical results show that the higher this share, the closer the common property and private property solutions.

4.4 Linking Sub-System Models

Sub-systems of bio-economic models have been integrated into single models in situations where it is appropriate and/or expedient to minimize the amount of analytical detail. There are an abundance of biophysical-technically oriented bio-economic models in which the economic detail is simplified, usually assuming a perfect neo-classical market model. Likewise, there are an abundance of economically oriented bio-economic models in which the biophysical-technical detail is simplified, usually into a single function in which production depends upon a single control variable and a single stock variable. Sometimes, however, these models provide insufficient decision support for policy guidance (Brown, 2000). This would be true for most cases of policy to facilitate sustainable intensification in developing countries.

The alternative is to link several detailed sub-system models, either employing a single model as a link or an integrated framework. Both of these methods provide ways of creating a common denominator among disparate measures[19]. Bayesian network, systems dynamics, and agent-

[19] Benefit-cost analysis also provides a form of link for sub-system models in that monetary units provide the common denominator of the linkage (Kragt et al., 2010).

based models have been used to provide single linking models. Bayesian network models have been used in situations in which it is the discrete, non-continuous, nature of ecological and/or economic processes--break-points and thresholds--and uncertainty that are the focus of study (Heckbert et al., 2010; Kragt et al., 2010; Whitten and Bennett, post 2004). Systems dynamics and agent-based models have been used as links in integrated modeling systems where the biophysical-technical and economic sides of the bio-economic system are dynamic (Heckbert et al., 2010). As agent-based models were addressed in section 4.2.4 and Bayesian network models will be discussed in section 4.5, only systems dynamics models will be addressed as single linking model in this section.

In integrated frameworks, models are linked hierarchically in a chain with the output of models lower in the hierarchy being used as input into higher models. Such input may be used, for example, for parameterization. The common denominator between models is provided by assuring communication or compatibility between models (Keating et al., 2003; van Ittersum, 2009). Integrated frameworks integrate institutions as one of several sub-system models. This institutional model may be fully integrated into the hierarchy or it may be the sole isolated sub-system model. An example of the latter is provided by the System for Environmental and Agricultural Modeling: Linking European Science and Society--Integrated Framework (SEAMLESS-IF), described below.

4.4.1 Linking Models: a Systems Dynamics Model

Systems dynamics (SD) models are constructed from structural equations with feedbacks. They are frequently used to model complex, dynamic ecological systems, and have been used to connect sub-systems, such as the biosphere, hydrosphere, atmosphere, and the anthroposphere, to build integrated full bio-economic system models (Heckbert et al., 2010).

Mongruel et al. (2011) provide an integrated full bio-economic system systems dynamics model, applied to the problem of overexploitation and possible drying up of common-pool freshwater resources provided by river catchments and their associated ecosystems in coastal south-western France. There were three types of user conflict over the freshwater resources: (1) between two extractive uses (crop irrigation and drinking water); (2) between extractive uses and other ecosystem service uses (shellfish farming[20] and recreational fishing); and (3) within each of the two production sectors (agriculture and shellfish farming). The conflict within the agricultural sector was between up-stream and down-stream users of freshwater for crop irrigation.

The government regulations that were in place restricted freshwater use for crop irrigation through access rules calibrated to critical discharge levels at monitoring stations. However,

[20] Shellfish farming relies on river nutrients for oyster growth and freshwater for spat production (Mongruel et al., 2011).

additional measures were needed. The alternatives were either scheduled rationing (users access allotted annual use-rights distributed over segmented periods) or a collaborative irrigation scheme (users take turns pumping on alternate days when the alert threshold has been reached). The latter was proposed by local stakeholders as a “soft institutional” solution that did not involve restrictive top-down measures enforced by government; and it had been employed voluntarily by some upstream users due to social pressure from some downstream users, but it had not yet been employed by any downstream users.

Thus, the three institutional arrangements to be modeled were: annual use-rights (access to the entire annual use-right at any time), scheduled rationing, and a collaborative irrigation scheme. The three institutional solutions were each integrated into the systems dynamics model as exogenous parameters. The first two were integrated into the model through a parameter that defined the level of temporary irrigation limitations at each time step (0 or 1); the last was integrated as a constraint on the equation for farmer irrigation demand. The model’s sub-system modules were: hydrological, agricultural, oyster growth, and governance. There was differentiation between upstream and downstream irrigators. Model simulations were run for the different combinations of the three institutional options as applied to the two types of irrigators, for both normal rainfall and dry years. Simulation scenarios were run using a computer software program for one sub-basin of the ecosystem.

It was found that crisis events could be avoided in normal years if scheduled rationing was implemented with both upstream and downstream irrigators, and the most efficient institutional solution for both normal and dry years was implementation of the collaborative irrigation scheme by both types of irrigators. It was noted that resolution of inter-sectorial conflict in the agricultural sector would mitigate the stresses on the common-pool freshwater and thus broader conflicts over freshwater use in the ecosystem.

4.4.2 Integrated Frameworks

van Ittersum (2009) provides an example of an extensive integrated system: the System for Environmental and Agricultural Modeling: Linking European Science and Society--Integrated Framework (SEAMLESS-IF). SEAMLESS-IF is a computerized framework and interactive software package comprised of a seven-model integrated chain as shown in Figure 6, that extends from a model that simulates agricultural externalities to a global trade model. SEAMLESS-IF is designed to be used by scientists and policy makers in conjunction with modelers to make ex ante predictions of the outcomes of change in agro-environmental policy. It has been applied to an EU trade liberalization scenario (Adenauer and Kuiper, 2009) and the extension of the EU Nitrate Directive from vulnerable zones to the entire Midi-Pyrenees region of south-west France (Amblard et al., 2009).

SEAMLESS-IF integrates institutions into the bio-economic framework through the use of the Procedure for Institutional Compatibility Assessment (PICA). Unlike the other six models in the integrated framework, PICA is outside of the direct communication chain: there is no direct output from other models into PICA and PICA provides no direct data into other models. PICA is not in fact technically a model; it is a procedure--aided by a software package--that is comprised of four steps with screens that lead a modeller through a process for assessing the compatibility of a policy option with the existing socio-economic, institutional and governance context across a range of geographic scales. Various data sources and methods of data collection are employed, and the procedure provides prompts with lists of potential responses at each step. PICA's four steps are: (1) classify the policy type in terms of its instrument (regulatory, economic (dis-)incentives, or advisory/voluntary), targeted governance structure (government, market, or self-organized networks), and potential implications for property rights change; (2) identify critical institutional aspects (CIA) that might foster or constrain implementation of the policy; (3) determine quantitatively and qualitatively the extent or relevance of each CIA; and (4) make a qualitative assessment of the overall compatibility of the proposed policy with the existing broad socio-economic, governance and institutional context. Once CIAs are identified and assessed, specific potential ways to modify the policy to increase its compatibility are explored (Ewart et al., 2011, 2009; Hagedorn, 2008, 2013; Janssen and van Ittersum, 2007b).

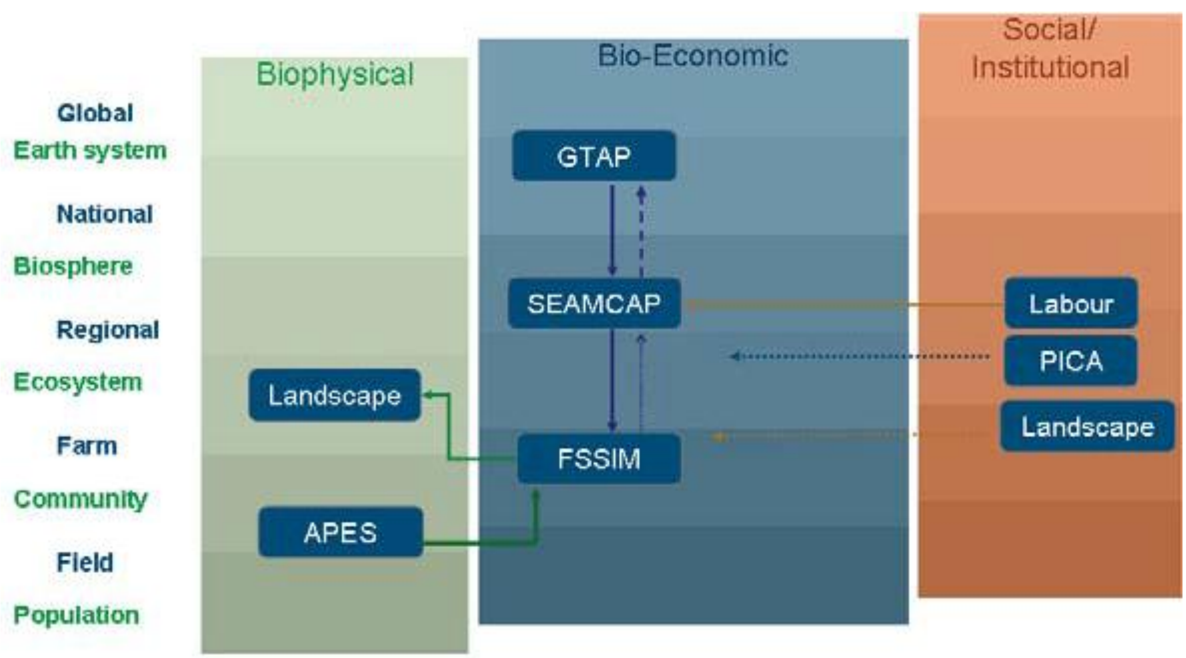

Figure 6 Modular components of SEAMLESS-IF (Source: van Ittersum, 2009)

Amblard et al. (2009) provide an application of SEAMLESS-IF's PICA for ex ante assessment of the policy to extend the implementation of the EU Nitrate Directive (1991) in the Midi-Pyrenees region of south-western France from its 1994 application target of the producers located solely in the region's vulnerable zones to the entire region. The extension was justified by evidence that a reduced water level had increased nitrate levels dangerously in the associated Adour-Garonne watershed that drains into the Bay of Biscay. The EU Nitrate Directive under analysis stipulated uncompensated, mandatory rules in targeted areas for manure control (through the use of storage sheds) and fertilizer application (seasonal schedules and rates).

Use of PICA provided modellers with evidence to conclude that although producers valued environmental conditions in general, the combination of several factors meant that lack of producer compliance would likely sabotage the policy as it was currently designed. Those factors were: producers' low level of awareness of and concern about water pollution in the area coupled with producer feelings of unfairness of the policy; the high level of bargaining power of farmers' organizations vis-à-vis environmental associations; and the high level of informational asymmetry between the local government and producers coupled with the lack of resources of the local government for environmental education and monitoring/enforcement. These findings of PICA were used to interpret and qualify validation of the predictions of the other components of the SEAMLESS-IF model-chain which had assumed costless institutional change and complete farmer compliance. It also provided information on the value of adding to the implementation of the EU Nitrate Directive specific measures to increase farmer compliance (Amblard et al., 2009; Schleyer et al., 2007; Theesfeld et al., 2010).

4.5 Choosing the Timing of Policy Change under Uncertainty: Policy Threshold Analysis and a Bayesian Network Model

Bayesian networks (BN) are probabilistic, graphical models with lines connecting nodes that represent variables. The different possible states of the nodal variables are identified either qualitatively or quantitatively, possibly through sub-system models. The lines between nodal variables represent the variables' one way causal relationships and the uncertainty of that relationship which is described as a conditional probability distribution at one point in time or at a net steady state point[21]. Join probability distributions can also be incorporated. BNs can be represented as conditional probability tables which express "the probability that a certain state is observed at *every possible combination* of the input variables" (Kragt et al., 2010).

BNs are appropriate for modeling a full bio-economic system when the focus of analysis is on uncertainties and the acyclical discontinuities, break-points, or thresholds of biophysical-technical, economic, or institutional/governance processes; and, system dynamics or feedbacks

[21] It should be cautioned that this uncertainty can originate from parameter, natural variation, or specification of the causal structure itself (Barton et al., 2008).

are not a focus. They are appropriate for integrated assessment because they facilitate the combination of information from various sub-systems of a full bio-economic system into a single decision-support model. One use of BN's has been modeling natural resource management under uncertainty. The main limitation of BNs models are that they do not represent interactions or feedbacks, and they are not dynamic (Barton et al., 2008; Kragt et al., 2010; Whitten and Bennett, post 2004).

Policy threshold analysis[22] is a tool for identifying the optimal timing of policy change under conditions of uncertain biophysical thresholds. The analysis is based on identifying the point in time at which the benefits of policy change are greater than the costs. The costs under consideration are the costs to both stakeholders and the government, including the real and transaction costs of the process of policy change—policy choice, development, implementation, and enforcement--as well as the policy's implied resource reallocation. Central to the analysis is the calculation of quasi-option values of acting now or postponing the policy decision to obtain more information to reduce uncertainties, both in the context of the potential for reaching uncertain biophysical thresholds in the interim. These uncertainties mean that policy targets are ranges rather than single optimal points (Whitten and Bennett, post 2004).

Key factors in the timing decision are the degree of information completeness and certainty of both benefits and costs, as well as the degree of potential for the existence of an environmental impact threshold (positive or negative) and/or irreversibility, which would create discontinuities in the model and potentially increase the costs of delay. Sensitivity analysis is used to identify the impact of uncertainties on outcome values, the range of potential net benefit outcomes, and the parameters with the greatest impact on net benefits. One advantage of policy threshold analysis is that it only requires that policy makers have enough information to qualitatively asses the scales of the relative transaction costs of policy options, and not their absolute costs.

Whitten and Bennett (post 2004) offer an example of the use of policy threshold analysis based on a full-system Bayesian Network bio-economic model of wetlands with threatened species on private lands in Australia. Their policy threshold analysis began with identifying: the environmental goals, the associated management changes and their benefits and costs (including transaction costs) to land owners, the policy options to leverage management changes [23], and the transaction costs to government associated with each policy option[24]. The overall transaction

[22] Policy threshold analysis is similar to threshold value analysis in benefit-cost analysis (Whitten and Bennett, post 2004).

[23] For example, upon analysis of a facilitated-voluntary policy, it was found that the up-front costs to land owners of making the change was higher than total benefits, but the ongoing costs of maintain the change were less than the ongoing benefits. So, the policy instrument considered was a subsidy to those prohibitive fixed up-front costs (Whitten and Bennett, post 2004).

[24] To facilitate comparison, policy transaction costs were assessed on a relative scale (low, medium or high). Government policy transaction costs included: design information, enactment, implementation, administration,

costs of each policy were assessed using weights[25] for the various transaction costs and sensitivity analysis of the weights. The overall cost-effectiveness rating of each policy option, including business-as-usual, was assessed taking into consideration the relative overall transaction costs and relative degree of biophysical wetland protection effectiveness. Those policy options with high overall transaction costs and low to medium biophysical wetland protection effectiveness were given an "unlikely" cost-effectiveness rating, thus warranting no further consideration. Those with low overall transaction costs and medium to high biophysical wetland protection effectiveness were given a "likely" cost-effectiveness rating, and might warrant further investigation to determine absolute transaction costs. However, policy makers needed to weigh the benefits of taking additional time to gather information against the possible species losses if an extinction threshold is breached in the meantime.

detection, prosecution, and risk. Market policy transaction costs included: direct costs, additional information, contracting and detection and protection. Also considered were dynamic impacts on transaction costs of change in exogenous factors in terms of incentives for innovation in management to improve environmental benefits, reduce costs, and increase flexibility (Whitten and Bennett, post 2004).

[25] The weighting scenarios included: base case, equal (policy) group type, equal cost, administration weight halved, current transaction costs weight halved, and current transaction costs weight doubled (Whitten and Bennett, post 2004).

Table 2 Integration of Institutions in Bio-Economic Models
(Sources: Brown, 2000; Heckbert et al., 2010; Janssen and van Ittersum, 2007a; Prellezo et al., 2010; Upadhyay et al., 2006)

Table 2 Integration of Institutions in Bio-Economic Models				
Model	Pros	Cons	Particular Applicability (Example)	Depiction of Institutions
Standard Optimization $Y=\max\sum_{1}^{n}\alpha_1 x_1$ s.t. constraints	Optimization Equilibrium Heterogeneity	No dynamic feedbacks (but, can discount)	(Chantarat and Barrett, 2012)	Parameters Constraints Elasticities Non-separability
Bayesian Network (nodes linked by probabilities, or joint conditional probability dist.) x_1___39%___x_n	Models risk Qualitative & quantitative data Vars. w/break-points & thresholds Limited heterogeneity	No dynamic feedbacks Need probability data (data quality issues)	Discrete processes Uncertainty Used as a linking model (Whitten and Bennett, post 2004)	Nodes Non-explicit contribution to probability & uncertainty
Systems Dynamics (structural equations) $\Delta X=\alpha.X-\beta.X.Y$ $\Delta Y=\gamma.\beta.X.Y-\delta.Y$	Dynamic feedbacks Stocks, flows Heterogeneity	No autonomy No adaptability/ learning	Used as a linking model (Mongruel et al., 2011)	Parameters
Evolutionary $\max_{\{k:\eta jk(t)=1\}} A_{kt}$ $A_{j(t+1)}=A_{k^*(t)}$ $\tau_{j(t+1)}=\tau_{k^*(t)}$	Dynamic Feedbacks Heterogeneity Can interact Can adapt/learn Can model risk Can evolve	No autonomy	Long time scale (Fogli and Veldkamp, 2013)	Parameters
Agent-Based (Multiple decision-making functions & parameters) $\Pi_{j,i,t}=$ $(O_{j,i,t}*Q_{j,i,t}*P_i)-$ $(FCi+VC_i*Q_{j,i,t})$ $+ FPR_{j,t} - FPC_{j,t}$	Non-equilibrial Dynamic feedbacks Can evolve Autonomy (rule based) Heterogeneity Adaptive decision-making Accommodate complexity	Current lack of theoretical underpinnings	Provide quantitative explanations Scaling up Used as a linking model (Heckbert et al., 2011)	Parameters Dependent variable

5) Summary and Conclusions

The previous section demonstrated that there are many different means by which modelers have incorporated the different types of institutions into bio-economic models, and there are several different theories and model types that have been used in doing so. Reflecting on these means, theories and models through the lens of the generic bio-economic institutional model based on Ostrom and Cox (2010) and Williamson (2000) that was presented in Figure 4 of Section 3, we observe that there are several approaches to incorporation institutions into bio-economic models. Moving from left to right along the boxes shown in Figure 4, these approaches are to incorporate institutions into bio-economic models in one of at least five ways: resources (or a type of capital), constraints, factors affecting marginal incentives, factors structuring interactions—in market or non-market strategic contexts--and/or the outcomes of social choice processes.

Given the “fixed pie” nature of the inevitably limited operational and data capacities of bio-economic models, the different approaches inherently imply a tradeoff between the complexity of their depiction of reality of institutional and biophysical-technical phenomena. Different types of tradeoffs are appropriate depending upon the problem setting and the purpose of the model. Pertinent aspects of the problem setting are whether more of the complexity of reality of the problem setting is in the biophysical-technical or the institutional side. Pertinent aspects of the purpose of the model are whether its purpose is to generate general hypotheses or specific predictions of cause-effect, and whether it is to be used to generate relative assessments or exact quantitative measures.

The paper concludes with a review of its main contributions towards the incorporation of institutions into bio-economic models of sustainable intensification of agro-environmental systems in developing countries. Hints for future model building efforts are also provided.

5.1 Summary of approaches for modeling institutions and their associated tradeoffs

1. Institutions as resources

The Community Attributes and Institutional Conditions boxes displayed on the left side of Figure 4 depict the institutional arrangements that shape the Action Situations of an individual resource user. Section 3.4.1 described these conditions in terms of the social, political or institutional capital that an individual can use as leverage in an Action Situation. To the extent to which social, political or institutional capital can be accurately measured, it can be incorporated in a bio-economic model as a factor of production. For example, various studies have recently attempted to measure the extent of an individual’s social networks that are employed for different purposes (Banerjee et al., 2013). Several studies of social networks were reviewed in Section 4.2.3. One challenge with treating social capital as a resource in bio-economic models is that social capital is generally non-rivalrous; that is, using social capital for one use may not mean that there is less social capital available for other uses. Indeed, the use of social capital for one purpose can potentially increase the amount of it that is available for another use. This attribute of social capital means that behavior in one sector can be re-enforced through social networks in another sector. This could be an advantage or disadvantage to the individual.

2. Institutions as constraints

When viewed as fixed rules, institutions define the key elements of a bio-economic model, particularly the objective function (often discounted profits from an enterprise that accrue to a unitary decision maker), the resources available to that decision maker, and the constraints on allowable use of resources. For example, a regulation for water resource protection could be depicted as a quantitative constraint on the minimum stock of water that an irrigator is required to maintain in a reservoir. Sensitivity analysis can be used to understand how sensitive model results are to changes in those fixed rules. This approach to incorporating institutions focuses on the linkages between the Institutional Conditions and the Action Situation as presented in Figure 4. The data demands for this approach tend to be fairly straightforward, rules or policies need to be well understood and clearly related to the behavior of the unit under consideration. As there is a need to aggregate individual behavior to the behavior of a collective (see Section 3.4), there may be a similar need to disaggregate a collective constraint to the behavior of an individual. Especially in a developing country context, it is important to distinguish between rules and policies that *de facto* affect individual behavior among the range of rules and policies that exist *de jure*. Legal pluralism research methods can be useful in this regard (Meinzen-Dick and Pradhan, 2001).

Depicting institutions as fixed rules is perhaps the most common approach for depicting the effects of institutions and policies in bio-economic models. There are several advantages associated with this approach. First, it focuses attention on the most important consequences of a specific institutional arrangement within a specific decision-making context. Second, because it is simple, it allows a modeler to focus scarce modeling resources on other dimensions of the resource use context that may require more detail. For example, the modeler may be able to consider the consequences of water use constraints on different types of water users, or depict more complex biophysical-technical relationships such as the effects of different amounts of water during different phases of the crop growing season. The disadvantage of this approach is that it may not be appropriate for depicting market-based institutions, strategic interactions between resource users, spatial phenomena, or institutional change processes.

3. Institutions shaping marginal incentives

Bio-economic models offer other opportunities to incorporate the effects of institutions on the Action Situation described in Figure 4. As shown in the bottom box of the left side of Figure 4, Williamson's (2000) fourth level of institutions refers to Marginal Conditions that shape the

Action Situation. For example, some institutions are readily modeled through their effects on the marginal costs and marginal revenues that a resource user experiences as a result of unit changes in resource use. Taxes, subsidies, license fees, and travel costs can often be depicted simply through either the specification of parameter values in an objective function (affecting costs or revenues), or through the combined specifications of both objective function parameter values and constraints.

Some more fundamental institutional arrangements – which would be characterized as Community Attributes in Figure 4 -- can be depicted adequately through specific parameterization of the objective function. For example, the effect of a fixed-share contract between a landlord and a tenant can be evaluated through cost and revenue share parameters on an objective function. Comparative static analysis can then be used to evaluate the effects of changes in those shares. This approach to depicting institutions in bio-economic models has similar advantages and disadvantages to the fixed-rule approach: its relative simplicity allows model builders to apply scarce modeling resources to other dimensions of the decision process, but it is limited in its ability to address other aspects of the institution under study. Such other aspects might, for example, be the oft noted quality of sharecropping as not only a tenancy arrangement, but also an arrangement for sharing risk and coping with credit market constraints (Otsuka and Hayami, 1988).

4. Institutions providing the structure for different types of interactions

a. Market interactions

The portrayal of Interactions among agents requires a considerable increase in the complexity of depiction of farmers' decision making processes as well as the bio-economic models built to understand the effects of those processes on Outcomes and, *via* feedbacks and learning, Action Situations. For example, the availability of a spot market for the exchange of irrigation water with other water users means that a farmer faces multiple simultaneous decisions – how much to produce, what technology to use, how much water to sell to others, and how much water to purchase from others (Carey and Zilberman, 2002). Such multiple simultaneous decisions also arise with the establishment of a spot market for the exchange of fertilizer pollution permits (Heckbert et al., 2011). The effects of uncertainty, irreversibility and the option to wait can be incorporated into models through option value theory as described by Dixit and Pindyck (1994) and policy threshold analysis as described by Whitten and Bennett (post 2004).
The obvious advantage of this approach is that it can allow modelers to examine decision making processes and resource allocation outcomes under more realistic institutional and market contexts. Different types of input markets can be depicted, as well as different types of farmer decisions. This greater reality comes at the expense of increased complexity and data demands, however, which considerably increase requirements of time and care in model construction and parameterization. Perhaps the most realistic and useful models are those that have been

developed through the sustained efforts of a small group of modelers, utilizing the best available techniques and data. David Zilberman has worked with a number of colleagues and PhD students at the University of California over many years to develop a series of models of water management in the Central Valley of California, producing outputs from 1985 through to the present day.

a. Strategic interactions

Dynamic stochastic programming is also employed in models that depict the strategic interaction between agents who share access to a resource, with different institutional arrangements underlying the strategic relationship between those agents. Game theory is often used to depict the cooperative or non-cooperative nature of these strategic interactions. For example, Swallow and Bromley (1994) developed a dynamic stochastic model of an African rangeland to examine the possibilities for success of a co-management arrangement in which resource access was control by the state and implicit contracts between agents were enforced by expectations that other herders would respond to one's own stock rate decisions. Extensions to this type of model take into consideration that monitoring others' behavior is costly (Rustai et al., 2010). These types of models can depict highly stylized property rights and resource user situations, but they become very complex if the modeler attempts to incorporate very much complexity in terms of the types of resource users or biophysical-technical relationships. Data on strategic motivations and behaviors is rarely easily observable, but can be generated using techniques such as experimental economics and stated choice experiments (Heckbert, 2009).

b. Heterogeneous agents interacting across geographic or social space

Given the limitations and challenges involved in constructing optimization models, such as the stochastic dynamic models developed by David Zilberman and colleagues, it is little wonder that analysts have looked to other modeling approaches to deal with more complex situations, such as those in which heterogeneous agents interact across geographic or social space. Agent-based models, which typically generate information about the tradeoffs associated with alternative scenarios, rather than optimal solutions *per se*, have emerged as the main alternative to optimization models for meeting this challenge (Barton et al., 2008; Epstein, 2006; Kragt et al., 2010; Whitten and Bennett, post 2004). A significant advantage of agent-based models is that they can cope with more biophysical-technical and spatial complexity than most dynamic optimization models. Another characteristic of agent-based models is that they do not focus on long-term equilibria, as do optimization models, but instead on the evolution of systems. Epstein (2006) proposes that agent-based models offer opportunities for a new type of "generative" social science in which hypotheses are generated by the model, rather than a model being based on hypotheses about human behavior. One disadvantage of agent-based models is that as of yet there are no particular theoretical underpinnings to calibrate or evaluate models, such that it is left to individual analysts to decide how to assign decision rules for agents.

5. Institutions as the outcomes of social choice processes

The norm in bio-economic modeling is to take institutions as a given, and then evaluate resource outcomes under different institutional arrangements, perhaps through sensitivity or scenario analysis. An alternative approach would be to assume that institutions are fixed in the short-term, but influenced over the longer term through feedback loops, as depicted in Figure 4. The concept of institutional evolution or induced institutional change was developed by analysts such as Demsetz (1967) and applied to water management institutions in the United States by Anderson and Hill (1975). This theoretical approach assumes that changes in institutions are the outcome of social choice processes, and that there are both fixed and variable transaction costs associated with institutional change. Whitten and Bennett (post 2004) applied this theoretical approach in a bio-economic model of policy thresholds in an attempt to explain the evolution of institutions for the management of private wetlands in Australia. Beyond the Whitten and Bennett (post 2004) paper, we were not able to find other examples in the literature of this approach.

Table 3 Approaches to Modeling Institutions and their Tradeoffs

Table 3 Approaches to Modeling Institutions and their Tradeoffs			
Approach: Institutions as …	Tradeoffs		Examples
	Pros	Cons	
A Resource, part of social capital, or a 6th type of capital	Relatively low complexity and data demands of the institutional side of the model frees up modeling resources for depiction of greater complexity in the biophysical-technical side of the model.	Relatively low fit with reality tends to decrease accuracy for policy guidance.	Chantarat and Barrett (2012) Fogli and Veldkamp (2013)
A Constraint			
Expressed as a "fixed-rule"			Heckbert (2011) Mongruel et al. (2011)
Expressed as a Factor Shaping Marginal Incentives (e.g., taxes, subsidies etc.)			Heckbert (2011)
Providing the Structure for Interactions	Relatively high fit with reality tends to increase accuracy for policy guidance.	Relatively high complexity and data demands of the institutional side of the model may prevent modeling resources from being available for greater depiction of complexity in the biophysical-technical side of the model.	
Structuring Market Interactions (determinants of market conditions and price dynamics)			Carey and Zilberman (2002) Heckbert (2011)
Setting the Context for Strategic Behavior (Game Theory)			Fernandez (2006) McCarthy et al. (2003) Narloch et al. (2012) Ngo and Wahhaj (2012) Swallow and Bromley (1994)
Setting the Context for Heterogeneous Agents Interacting Across Geographic or Social Space (Agent-Based Models)			Heckbert (2011) Whitten and Bennett (post 2004)
Outcomes of Social Choice Processes			Whitten and Bennett (post 2004)

5.2 Conclusions about the incorporation of institutions into bio-economic models of sustainable intensification in developing countries

Overall, we believe that this paper makes several contributions to the collective international research effort to use bio-economic modeling to promote sustainable intensification of agricultural and natural resource management in developing countries.

Section 2 provides some clarity about what we mean by 'institutions' and why institutions are important for sustainable intensification. In sum, institutions structure the allocation of resources and management responsibilities, individual's access to and use of resources, their interactions and transactions with each other, and their interactions with groups or government agencies. Section 2 also describes some of the common features of developing country agricultural systems, several of which make the construction of bio-economic models more complex than in more developed country contexts. Household models that integrate production and consumption, for example, may be especially appropriate for modeling developing country situations. Bio-economic models can be employed to analyze the impacts of technologies, policies and institutions on the sustainability of systems, particularly with respect to examining impacts of outcomes on the quantity and quality of natural resources.

Section 3 describes a framework that matches the key elements of bio-economic models with the key elements of institutional analysis. That framework can contribute to bio-economic modeling of sustainable intensification in two ways. First, it clarifies important elements of the institutional context that should be considered in the construction of a bio-economic model. That institutional context should be kept in mind by analysts themselves as well as readers who are contemplating the applicability of model to other circumstances. Second, the framework identifies specific opportunities for explicitly incorporating institutional phenomena into bio-economic models. Section 5.1 discusses ways to operationalize those.

The paper shows that the depiction of interactions is especially challenging for bio-economic models based on optimization and equilibrium. Depicting strategic interactions in such models – through adjustments in market prices or through the updating of strategies based on observations of others' behavior – are quite challenging (e.g., dynamic stochastic programming). That complexity may be one reason why some analysts are turning toward agent-based modeling as an attractive option. Because agent-based models focus more on process, they may be particularly appropriate for the study of sustainable intensification. More explicit incorporation of institutions into agent-based models may be a fruitful area for future research.

An apparent gap in the current literature on bio-economic modeling relates to the depiction of feedback processes between outcomes and institutions. The only paper that the authors found that addresses these feedbacks (Whitten and Bennett, post 2004) is not published in the peer-reviewed literature.

Going forward, we propose that analysts interested in incorporating institutions into bio-economic models for particular situations should consider the following suggestions.

1. Clarify the theoretical foundations of empirical models

Whenever possible, build empirical models that are consistent with accepted ecological and social science theory. This does not mean that model builders should be satisfied with accepted assumptions that are inconsistent with observation, such as the assumption of perfectly competitive markets and zero transaction costs. Institutional and behavioral economics have developed over the last 20-30 years to better capture more complex behaviors, market imperfections, and transaction costs.

2. Look for the easiest ways to simplify institutions into constraints and parameters

Models that capture institutional phenomena as specific constraints or parameters in marginal incentives can often yield very clear insights into human behavior without overly complex constructions. Theory can often be used to justify the choice of constraints or parameters, such as a share tenancy parameter or an index of inequality in bargaining power in intra-household decision making. Models that are very efficient in depicting institutional phenomena can better lend themselves to more complexity in the way that they depict biophysical-technical relationships. Sensitivity or scenario analysis can often be used as a replacement for more complex models.

3. Use new tools, such as social network analysis and experimental economics, to characterize behavior that is difficult to observe

There has been rapid development of empirical methods for characterizing behavior that is difficult to observe such as intrinsic motivations, the values of non-market goods and services, responses to uncertain decision contexts, and social networks. Many of these methods can be used to generate parameters or rules that can be used in bio-economic model construction. Such tools may be particularly relevant for the construction of agent-based models.

4. Sustain and integrate modeling efforts

One problem that is frequently noted among bio-economic modelers is that model building efforts are fragmented and models are constructed in ways that are difficult to reproduce. In the light of this observation, it is interesting to consider the success of the efforts by David Zilberman and colleagues at the University of California-Berkeley in modeling the irrigation systems of the Central Valley of the United States, or the efforts of the SEAMLESS-IF project in modeling agro-environmental systems in Europe.

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