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Approaches for analysing trade-offs between productivity, nutrition and environmental outcomes at multiple scales

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ABSTRACT

Biodiversity affects the stability of ecosystem services, which in turn affects agricultural productivity and therefore global food security. The nature of the linkages between biodiversity and food security vary across temporal and spatial scales and are influenced by socio-economic drivers of agricultural systems. Based on existing literature, this paper outlines the relationships between biodiversity, ecosystem services and food security. It additionally reviews tools which can be used to integrate biodiversity and ecosystem services into analytic frameworks to allow a better understanding of the trade-offs between different agricultural systems and their ecosystem services provisioning, as well as the resulting impact on productivity and human well-being.

Keywords: *trade-off*, Agricultural systems, Ecosystem services, Model integration

PAPER

1. Introduction

There is increasing evidence that plant biodiversity increases ecosystem services (ESS) stability (Hautier et al. 2015), and that selection of appropriate land-use patterns and agriculture management practices not only increase productivity but also mitigate and enhance adaptation to climate change (Powers 2010; MA 2005). Conversely, poor production and management choices lower agricultural productivity and food security as a result of degraded land, scarcity and reduced quality of water, increased pest and disease risks, and loss of natural pollinators. Given this relationship between the health of ecosystems and economic development, including food and nutritional security, the global community adopted a sustainable development agenda at the 2015 UN General Assembly (UN 2015). This agenda includes the goals of sustainable agricultural production (under Goal 2); management of water (Goal 6); management and efficient use of natural resources (Goal 12); and protection, restoration and promotion of sustainable use of terrestrial ecosystems (Goal 15). The CGIAR similarly identifies improving natural resources and ecosystem services (ESS) as one of its high-level outcomes in its Strategy and Results Framework (CGIAR 2015) and has adopted a systems approach for its 2016-2022 research agenda. The establishment of these global development goals and frameworks for actions provide an opportunity to fully integrate biodiversity and ESS in the global agriculture research and development agenda, to not only improve food and nutritional security but also to achieve healthier agricultural ecosystems.

Understanding the multiple interactions between land use, management, environmental pressures and ESS is complex with interdependencies, trade-offs and tipping points. Understanding environmental, social and economic drivers requires transdisciplinary approaches. This paper explores some of the emerging approaches to integrate biodiversity and ESS into economic analysis of agricultural systems, particularly into those models designed to forecast the impact of potential investments and innovations on future productivity. Much of the discussions in this paper are based on a workshop convened at Bioversity International May 2015 (Rojas et al. 2015). In the following section, challenges faced in integrating biodiversity and ESS in economic models are discussed. The conceptual framework is then presented, highlighting the link between cropping patterns, practices and environmental outcomes. The next section discusses bio-economic models at different scales (from local to economy-wide). The paper closes with some discussions and conclusions for further work.

2. Challenge in integrating biodiversity and ESS in economic models

The productivity of agricultural ecosystems depends on ESS provided by natural ecosystems (Power 2010). According to the global initiative The Economics of Ecosystems and Biodiversity (TEEB), ESS are the flows of value to human societies as a result of the state and quantity of natural capital (TEEB 2010). The Millennium Ecosystem Assessment (MA 2005) describes four categories of ESS: supporting services (e.g. soil formation, photosynthesis and nutrient cycling), provisioning services (e.g. fresh water, food, fuel and timber), regulating services (e.g. climate regulation through carbon storage and water cycling) and cultural services (e.g. recreation, spiritual, educational and aesthetic). Some examples of ESS related to agricultural ecosystems which affect productivity pertain to supporting services and include pollination, biological pest and disease control, maintenance of soil structure and fertility, nutrient cycling and hydrological services (Power 2010).

Biodiversity, among other factors, plays an important role in the provision of these services (MA 2005). Hautier et al. (2015) demonstrate a positive correlation between plant species biodiversity and ecosystem stability. Plant biodiversity affects soil nutrient content and therefore soil quality (Hajar et al. 2008; Ponisio et al. 2014; Mulumba et al. 2012). Selecting the right mix of crops rather than using one or a few dominant crops can dramatically increase crop water-use efficiency (West et al. 2014; Brauman et al. 2013). Biodiversity on farms and on landscapes provides broad genetic variations in plants and animals that is essential for adaptation and for resilience against future threats from pests and diseases (Heal et al. 2004; Hajar et al. 2008; Garrett and Mundt 1999). Increased crop diversity is shown to enhance pollinator health (Garibaldi et al. 2014; Isaacs and Kirk 2010). These ESS are also influenced by factors other than biodiversity and can be difficult to measure. Nevertheless there are ongoing efforts to identify metrics which can be used as indicators of these services (Biodiversity Indicators Partnerships 2015).

Biodiversity can be considered in two different contexts, intraspecies biodiversity and interspecies biodiversity. Intraspecies biodiversity is diversity within a single species while interspecies diversity is diversity of different types of organisms in a given ecological system. Both types of biodiversity are essential for stability in ESS and thereby for sustainable food production systems. The relevance of each biodiversity type, when used in analysis or in policy discussion, depends upon the scale at which the issue is being discussed or analyzed. The added complexity for analysis therefore involves consideration of context-specific types of diversity and the appropriate scale for the analysis.

Another important consideration from an economic and political point of view is the public goods nature of biodiversity and ESS. This means that they exhibit neither rivalry nor excludability. Rivalry refers to whether one agent´s consumption is at the expense of another agent´s consumption. Excludability indicates if some agents can be prevented from consuming a good by other agents (Perman et al. 2003). While some aspects of ESS such as pertaining to specific fields may be enjoyed privately by its owners, improved ESS resulting from preserving biodiversity can generally be enjoyed by all. Moreover, the costs of maintaining or enhancing agricultural biodiversity and ESS are usually incurred by individual landholders or operators and these are costs which occur in real time. The returns from these activities, which are enjoyed by all, however, may occur over a long period and may not cover the costs of the operator in the short term. Thus, inclusion of biodiversity and ESS into bioeconomic models requires addressing temporal and spatial challenges of private costs incurred in the short run for generating public goods in the long run.

Finally, the analysis of possible impacts of innovation, changes in biodiversity, and other interventions on ESS and, consequently, on agricultural productivity necessitates a systems framework and requires consideration across multiple scales. Interventions at the field and farm-level, including changes in biodiversity, affect the future flow of relevant ESS and, in turn, the agricultural productivity at any given site. Changes in policy or farm practices affecting the longer-term income potential of affected households, can cause a multiplier effect on future rural economy and even, in special cases, affect future national economy. Moreover, economically driven short-term land management decisions made by farmers at small scales can add up to drive ecological changes across whole landscapes across longer timeframes. Therefore, agroecosystems are intrinsically associated with natural ecosystems (Nicholls and Altieri 2004) and changes to agricultural landscapes affect the health of forests, wildlife, rivers, seas and other natural habitats. These changes in turn affect human activities and economic benefits associated with these habitats.

ESS depend on the interaction of multiple ecosystem types at different temporal and spatial scales, characterized by dynamic and non-linear relationships (Balbi et al. 2015; Bateman et al. 2012; Bennett et al. 2009), and the production of ESS in agricultural systems depends on the services provided by neighboring ecosystems (Power 2010). In recent years, significant strides have been made in analytic tools and computing capacity for work in this area (Rojas et al. 2015; Antle et al. 2015). These efforts have generally emerged from within different disciplines or, as in the case of integrated assessment models, have occurred in multidisciplinary teams. However, a concerted effort has not been made to model and study the trade-offs associated with agricultural production between productivity and environmental sustainability at multiple scales, taking into consideration agricultural biodiversity and ESS.

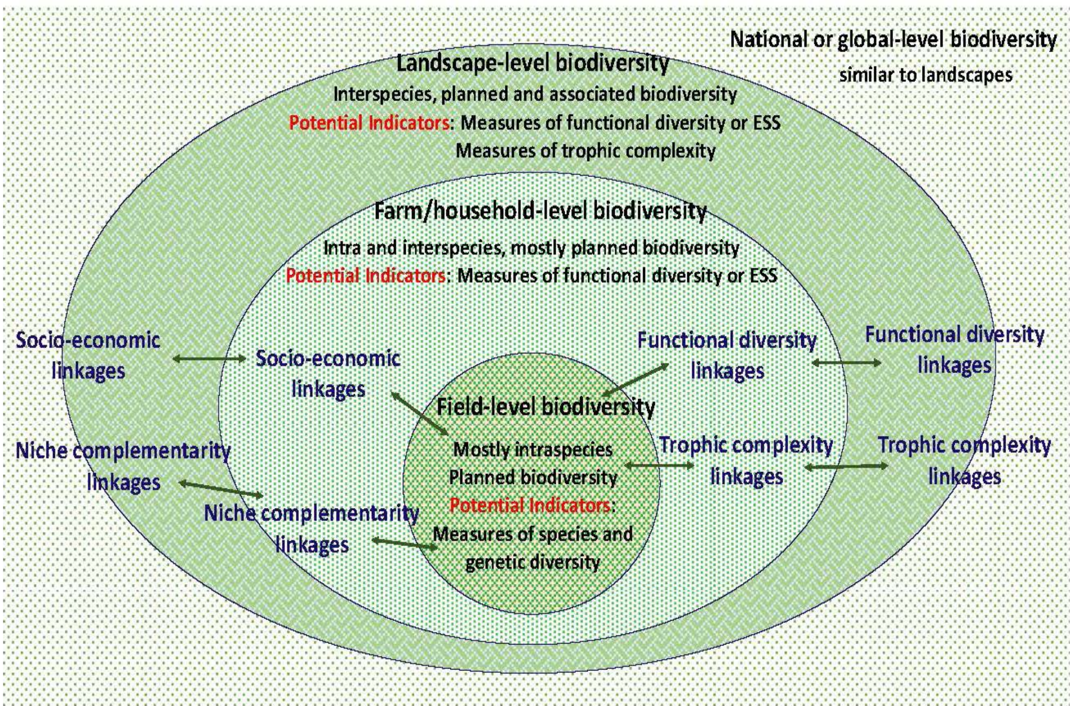
3. Conceptual framework for analysis

Nicholls and Altieri (2004) separated biodiversity in agroecosystems as *planned biodiversity* and *associated biodiversity*. Planned biodiversity is all life intentionally put in the ecosystem and varies with space, time, and other ecological conditions while associated biodiversity is all life that is attracted to, benefits from, and in turn contributes to planned biodiversity. The linkages between these are often established through *functional diversity*, the range of activities that organisms within an ecosystem perform. These include a variety of biological processes, functions or characteristics of a particular ecosystem, which connect a given agroecosystem to the health of the broader planned or associated ecosystems such as through ESS, for example soil quality, pollination or biotic and abiotic resilience. Another important linkage between planned and associated biodiversity is niche complimentarity which refers to the condition when different organisms use the same resource in different ways without directly competing with each other. Finally a third relevant aspect of connection between the two sets of biodiversity is *trophic complexity*, which indicates interactions between organisms at different levels of predation. These linkages between planned and associated biodiversity illustrate how the two systems, which could further extrapolate to socio-economic systems, are inter-connected. The precise relationships linking the two systems provide means of identifying measures for monitoring biodiversity and the possibility of using these measures as input in modeling exercises. For example, under certain conditions, information on soil quality, pollination, or a measure of trophic complexity can be used as either a reflection or an outcome of the existing status of biodiversity. The use of such measures would first need to be validated by studies which indicate their appropriateness for a given context.

Much of the past agriculture literature has tended to focus on planned biodiversity. Studies have mostly dealt with biodiversity within the context of 1 or 2 components of functional diversity, such as productivity (Li et al. 2009) or tolerance to biotic and abiotic stress (Costanzo and Bàrberi 2013). Yet it is known that practices on fields or a farm affect many components of biodiversity such as functional diversity, shift niche complementarity, and may consequently result in significant permanent changes to trophic complexity. Therefore models designed for the analysis of long-term agricultural productivity should consider analysis across multiple scales, taking into consideration the vertical linkages across scales as well as the horizontal linkages across sectors.

First at the field level, the effect of a choice of planned biodiversity on ESS and consequently its impact on productivity must be understood. At this level, activities and studies may focus on intra-species analysis, although inter-species is an important consideration in developing countries. Analyses additionally need to consider the connectivity between farm practices and non-cultivated areas within the farm and the impact of all practices on ESS (Fig 1). Second, how biophysical outcomes (including yield) of farming choices and practices affect social and economic dimensions are important aspects for consideration. These aspects may need to be examined at the farm or at the household level, with due consideration or incorporation of biophysical relationships. Third, the implications of choices made at the field and farm-level need to be fully examined at the agricultural sector level. This analysis needs to take into consideration how changes in planned biodiversity affect: the crop mix; implications for nutritional outcomes; the rural economy; and, as desired, the broader agro-economy and trade at the national and global level. Finally, agricultural sector level decisions and changes affect decisions, choices and outcomes in other sectors, including back on biodiversity and ESS. Also as earlier discussed, biodiversity status in planned agroecosystems affect biodiversity in associated non-agricultural ecosystems. Therefore the analysis of potential interventions at the field level need to be viewed within the broader economy-wide context.

Figure 1 – Conceptual framework for biodiversity assessment at different scales



As a basic conceptual framework any model designed for analysis of sustainable agricultural systems needs to incorporate the chain of linkages between changes in planned biodiversity and associated biodiversity, regardless of the scale of analysis. It is also useful to note that there can be multiple objectives along these chains, such as achieving food security, healthy diets, higher incomes, better livelihoods, resilient soils, sustainable use of water resources, and biodiversity in its own right as well as from a functional perspective. These outcomes occur at different scales. There are also multiple points at which interventions can be made, ranging from national-level interventions to field-specific interventions in agro-ecological systems.

Sustainable systems analysis needs to consider the choice of agricultural and land use activities and the resulting changes in linkage components such as functional diversity, niche complementarity and trophic complexity, and the trade-offs between these and the long-term productivity potential.

Using the concepts discussed by McGranaham (2014), such an analysis requires indicators of biodiversity measures at the field-level which can be related to functional diversity, and can be used as variables in most of the bioeconomic models. Measures of functional diversity associated with field-level changes in biodiversity are particularly well-suited in the analysis of field or agricultural sector models (Fig. 2). Among other indicators, functional diversity together with trophic complexity measures can be used as convenient indicators at the farm, household and economywide models. Given the current advances and efforts in data collection systems and data sharing platforms (Rojas et al. 2015; Antle et al. 2015), incorporation of appropriate indicators in modeling tools should be feasible.

Rojas et al. (2015) reviewed the literature to identify possibilities to harness existing capabilities to better incorporate biodiversity and ESS into economic analysis of agriculture systems. They developed a framework for assessing how well an existing model integrates these elements and whether there are scopes for improving it. Based on their approach, figure 2 summarizes key considerations in integrating biodiversity and ESS into analytic frameworks, with particular emphasis on linkages across scales and sectors.

Figure 2 – Conceptual framework for the model based assessment of the value of biodiversity

Vertical Linkages	Horizontal Linkages				
	Diversity-type		Assessment factors		Socio-economic consideration
Local-scale Field Farm Household Landscape	Mostly intra-species Intra and inter-species Intra and inter-species Intra and inter-species	↔	Crop yield, ESS Crop and livestock yield, ESS Food availability and demand, ESS Yield, ESS, community-level demand	↔	Benefits>costs at field level Joint benefits > joint costs at farm level Joint benefits > joint costs at household level Joint benefits > joint costs at community level
↕			↕		
Agricultural-sector	Mostly intra-species	↔	Relative demand, supply, prices nutrient, ESS	↔	Relative benefits/cost across commodities
↕			↕		
Economy-Wide	Intra and inter-species	↔	Relative demand, supply, and prices of food, and other consumer good; nutrition impact, ESS	↔	Impacts along value-chain, across commodities, across industry sectors, and across political boundaries

The conceptual framework, firstly, helps articulating linkages across scales and sectors. The effects of investments and interventions at the local scale, whether field, farm, household or local landscape, bubble up to higher scales and ripple across to other sectors. These linkages are not unidirectional. Changes made at the economy-wide level or at the agricultural sector level, for example a policy change, can in turn affect changes at the field, farm and household-level. The linkages in the analytic tool do not need to be hardwired into one single super-model. Rather, there can be soft linkages across models designed for different sectors and scales. Second, the framework helps to consider the requirements of modeling approaches designed for integrating biodiversity and ESS. This allows planning for necessary data collection during project design and implementation. Finally, given the existing linkages across scales, a key question in performing such analysis is whether the chosen approach allows for linking analysis across scales. It is likely that a modular configuration provides the versatility needed for adapting to different research objectives rather than one complex model with built-in linkages.

Assuming that a given modeling framework captures well the biophysical and socio-economic aspects, results from a given analysis must be examined within the context of other ongoing related work. Most models will rarely be able to integrate intra-household dynamics, particularly with respect to gender roles and decision making. Therefore the results from bioeconomic models must be examined with other ongoing analyses to explore gender and cultural aspects. Similarly models are simulated for certain selected scenarios and may not capture all complexities of all possible scenarios. Nevertheless, bioeconomic models are powerful tools for examining ex-ante and ex-post trade-off analyses between the impacts of a given innovation on productivity, nutritional outcome and ESS. The following sections briefly discuss the necessary steps in linking biodiversity to ESS, and integrating ESS into bioeconomic models at three scales of analysis as presented in figure 2.

4. Modeling the linkages between cropping patterns and practices to environmental outcomes

Agricultural economics profession has a long history of using different models which relate cropping patterns and practices to environmental outcomes. For example, Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model has been used in many earlier studies to examine the effect of agricultural practices and policies on groundwater (Boisvert et al. 1996). Models such as Soil and Water Assessment Tool (SWAT), which predict water availability and water quality have also been used in many studies (Douglas-Mankin et al. 2010). In recent years, there has been considerable effort within the biophysical science community to better understand the environmental impacts of cropping patterns and practices. Specific plot-level (Kumar and Nair 2007) and landscape-level (Swift et al. 2004) work has been undertaken to study the impact of agricultural biodiversity on environmental outcomes. In addition, there have been several concerted efforts to assess and value ESS. For example, TEEB has adopted a structured way to value biodiversity and ESS (TEEB 2010). ARIES, Artificial Intelligence for Ecosystem Services, provides a flexible suite of applications for mapping benefits, beneficiaries, and ESS flows (Villa et al. 2014). InVEST similarly estimates the biophysical provision of different ESS across a given landscape (InVEST 2015).

Bioeconomic models which are linked exogenously or endogenously (Janssen et al. 2010) to crop models can translate changes in ESS, crop-choices and management practices to crop yield. Many of these models use the DSSAT (Decision Support System for Agrotechnology Transfer) modeling system that comprises crop simulation models for over 28 crops (DSSAT 2015). Another common crop model is the Agricultural Production Systems Simulator (APSIM) software, a modular modeling framework which was designed to provide predictions of crop production in relation to climate, genotype, soil and management factors (Keating et al. 2003). Crop yields generated from such models can in turn be used as inputs to other bioeconomic models.

While efforts to estimate ESS from changes in biodiversity and land-use patterns are well-documented, these studies have not been systematically linked to economic analysis or always linked to specific field-level agricultural practices. Currently few analytical models capture complex behavior of (agricultural) ecosystems, and evaluate them at different scales (Balbi et al. 2015). Even simulation models, which take a more systems oriented approach, have focused on isolated processes and rarely examine effects of agricultural practices in multiple ecosystems (Balbi et al. 2015). Shepherd et al. (2013) conducted a review of data, from monitoring initiatives in sustainable intensification of agriculture, to examine past and ongoing efforts designed to inform decision-makers regarding trade-offs between food security, environment, and socio-economic goals. The authors identify weaknesses in many of the ongoing efforts but also point out that these weaknesses can be addressed. Among other solutions, they indicate the importance of data-sharing platforms to facilitate dissemination, reuse and learning. Similarly Antle et al. (2015) note that as growing demands are placed on agricultural ecosystems and landscapes, infrastructures are needed for supporting a comprehensive approach to data, knowledge, and its use for sustainable landscape management. The challenge therefore remains to leverage data, tools and skills present in the biophysical sciences to better link changes in crop choices and management practices to changes in the flow of ESS, which in turn affects productivity in subsequent years.

4.1 Bioeconomic models at local scale

Bioeconomic analysis at a local scale should include analyses of both productivity and environmental responses to varietal improvement or to other improved technologies. The impacts of a technology at a given locality can be analyzed at the field level, farm-level or at the household level, depending on the research purpose (Fig. 2). At the field level, the essential consideration in the past has tended to be whether, for a given crop, a given new technology is more profitable than the existing one. Farm-level analyses, similarly have tended to examine the profitability of a new technology taking into consideration all the enterprises on a given farm. While profitability and yield responses are important and essential considerations for wider adoption of a given technology, it is also important to analyze impacts on ESS to examine implications for long-term economic growth, environmental outcomes and sustainable food security.

Farm household models are a popular analytic tool for integrating household demand into the analysis of farm-level decision making (Louhichi et al. 2010; Kaimowitz and Angelsen 1998). These models are appropriate for analyzing the empirical relationship between farmer´s land use pattern, household preferences, and resource availability. They are capable of incorporating details regarding different crop and livestock systems and examining a number of technologies and potential impacts of a range of policy interventions (Louhichi et al. 2010). The models are particularly well-suited in applications regarding subsistence agriculture where production, labor allocation and consumption decisions are linked (de Janvry et al. 1991). These models can be applied to a single time period or over multiple years.

Figure 3 – Bio-economic models at local scale: strengths and weaknesses

	Strength	Weakness
Framework	Most operate using a 'bottom-up process' with the model based on detailed geophysical site-specific information.	Data requirement can be demanding.
Scope	It allows for site-specific trade-off analysis of productivity and environmental outcomes. Impact on human diets can also be incorporated.	Relating farm practices and crop choices to environmental outcomes can be difficult. Intra-household dynamics such as gender issues will need to be considered outside the model.
Domain	It is a good scale at which to analyze field-level activities in connection with farm or household level activities and try to link them to the immediate landscape.	Making these connections involves data issues. Some studies attempt to work with a few farms in a given landscape. Others start with large number of farms and reduce these to a few 'typical farms.'

Research has expanded to consider farm-level decision making within a landscape context. Given the scope for analyzing multiple benefits and costs, spatially explicit ESS provision modeling tools have increasingly become available. These tools describe multiple services or goals which a household or a farm can seek to optimize, such as agronomic, profit and environmental goals. These models are able to assess the impact of human activities on the provision and value of multiple services across space and time (Müller et al. 2010). At the moment however, the larger economic processes of market forces are often not incorporated in such models. Spatial models have high data requirements and limited spatial coverage, with infrequent capture of higher aggregation processes (Smeets et al. 2014).

Rojas et al. (2015) examined a number of farm and household-level models that are used for analyzing biodiversity and ESS. Based on this review, figure 3 presents their key strengths and weaknesses. While these models are useful to relate household-level decision making to its impacts, it is difficult to incorporate intra-household dynamics into the analysis. Factors such as gender-roles and nutritional impact on women and children, may need to be analyzed outside the models. Moreover, model scenarios must be selected and results interpreted taking into consideration these dynamics.

Given that the models are based on site-specific information, data needs can become cumbersome. There is also a challenge in deciding whether to make the model be true to a specific site or make the model more general and applicable across different sites. A possible solution is to adapt model prototypes, designed for specific farm or household typologies based on survey data, for use across different geographic sites covered by the same survey. Similarly, whether each component of the model, such as models for different crops considered, are endogenous to the model or exogenous can greatly change the level of complexity. It may be useful to design the model in a modular framework and enable linking different components as needed, rather than making a very complex single model which requires considerable investments for adaptation with each new use. However, a shared platform for data and for sharing analytic modules will significantly facilitate moving forward the research to allow integrating biodiversity and ESS into economic analysis.

4.2 Bioeconomic models at the agricultural sector level

Agricultural sector models belong to a set of models known as the partial equilibrium (PE) models which take into consideration only a part of the economy assuming the rest of the economy remains unchanged (ceteris-paribus condition). PE models incorporate both supply and demand of an industry or a sector of interest hence being able to capture market equilibrium processes. PE models are widely used for agricultural sector modeling because they offer the possibility of a comparatively detailed depiction of the sector while being comprehensive in spatial and commodity coverage and maintaining the capability of capturing market feedbacks taking place at relatively aggregate spatial scales. These models are powerful tools for assessing national/regional level policies, and also the impact of innovation within a commodity on the market price, demand and supply of other commodities.

Currently the agriculture economics profession has a wealth of information based on which model improvements can be undertaken to better integrate biodiversity and ESS into agriculture systems analysis. A commonly used tool IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) is a global multi-market, dynamic model that provides long-term projections (up to 2050) of global food supply, demand, trade, prices and food security (Flachsbarth et al. 2015; Robinson 2014). The model covers 58 agricultural commodities including livestock, fisheries, crop processing for sugar, oil seeds and cassava, and biofuels production. Globally, agricultural production is depicted at the level of 320 spatial units or food producing units (FPUs) based on 154 major river basins and 159 political regions or country boundaries. GLOBIOM is a global recursive dynamic model that integrates the agricultural, bioenergy and forestry sectors following a bottom-up approach based on detailed grid cell information on biophysical conditions, for agricultural production (including altitude, slope, soil characteristics, and the agro-ecological zone) and land use suitability, at a spatial resolution of 10 Km grid. Agricultural production is represented at a level of →200,000 spatial units (Havlík et al. 2014) for 18 globally most important crops, a range of livestock production activities, and forestry commodities as well as different bio-energy transformation pathways. Similarly MAgPIE (Model of Agricultural Production and its Impact on the Environment) a global, spatially explicit, recursive dynamic model uses a bottom-up approach and has a spatial resolution of 0.5°x0.5° which results in around 60,000 grid cells. This model covers 20 crops, 3 livestock, and 10 regions in the world (Lotze-Campen et al. 2010).

Figure 4 – Bio-economic models at the agricultural sector level: strengths and weaknesses

	Strength	Weakness
Framework	Most models are based on readily available national, global or regional data on production, trade and consumption and other uses. A few newer models are adopting the 'bottom up' approach of basing the model on site-specific information.	Integrating biodiversity and multiple ecosystem services to these models is relatively a new concept, and to date limited applications exist beyond some climate change analysis.
Scope	These models are well suited to examine inter-commodity market dynamics, both in local and global markets, including along value chains when included in the model, with changes in innovation or policy changes.	Relating farm practices and crop choices to profitability and environmental outcomes can be difficult. Intra-household dynamics such as gender issues will need to be considered outside the models. As the scope is limited to the agriculture sector, these models cannot directly consider impact on or from changes in other sectors of the economy.
Domain	These are relatively easy to use tools to compare the impacts of innovations across a number of countries and commodities, with simple disaggregation of bulk farm-gate product, semi-processed and processed products.	Relating environmental externalities can be incorporated in the models but currently the profession has limited applications. The models can be externally linked to household and economy-wide analysis, but this work is also currently under-developed.

While the above discussed models do not capture economic feedbacks between the agricultural sector and the rest of the economy (Fig. 4), agriculture sector models are an important tool and a necessary step for a comprehensive analysis of a given new innovation or a policy change within the agriculture sector. The model's aggregate spatial scale has limited representation and linkage with externalities and ESS, but model enhancements are being undertaken for greater consideration of site-specific biophysical information (Valdivia et al. 2012). For more comprehensive analyses, results from agriculture sector model can be linked to economy-wide models. In addition, results from analyses at other scales can be used to customize the model for specific scenarios.

4.3 Bioeconomic models at the economy-wide scale

The most common framework for analyzing innovation or policy changes using an economy-wide approach is the computable general equilibrium (CGE) model. These models cover production, consumption, input, and trade of all economic sectors for a given country, region or even for all countries worldwide. CGE models represent the optimizing behavior of all agents within the economy as producers, consumers, factor suppliers, exporters, importers, taxpayers, savers, investors, or government. This comprehensive coverage of economic processes allows assessing the full economic value to society of a public good such as biodiversity and ESS.

Important uncertainties and limitations to CGE modeling analyses are that the high level of aggregation conceals variations in and economic interactions between the underlying elements, and limits the degree to which bottom-up information and data can be effectively integrated within the larger model. Often the representation of specific commodities or agricultural technology and technological change can be limited. However, advances on bioenergy analyses have been made in some Global Trade Analysis Project (GTAP) model versions (Smeets et al. 2014), as well as assessments of ESS and biodiversity using CGE ICES (Intertemporal Computable Equilibrium System) model (Bosello et al. 2011).

Figure 5 – Bio-economic models at the economy-wide level: strengths and weaknesses

	Strength	Weakness
Framework	Model is based on aggregate national accounts data which is readily available.	High-level of data aggregation in the model only allows impact analysis at a very aggregate level.
Scope	It allows for analysis across all sectors of the economy, producers, consumers, suppliers of factors of productions, exporters, importers, taxpayers, investors, government. As such, it will also allow taking into consideration the impacts of biodiversity and ESS outside the agriculture sector.	As a complete consideration of biodiversity and ESS into such a model has not been attempted before, it will be a big challenge to develop the necessary data to include them into the model.
Domain	Given the public good nature of biodiversity and ESS, these models will capture comprehensively their economic value to society.	The model will not be able to capture the 'intrinsic value' individuals may place on biodiversity and ESS to just conserve them for future generations. As such it is likely that the estimated value will be an under-assessment of the true value.

Similar to the advances in agricultural sector models, significant advances have been made in CGE models. The recent version 8 of the GTAP database contains 57 commodities and 129 regions, including up to 12 agricultural commodities on the supply side and seven on the demand side. The forestry sector is included through a forest products commodity (GTAP 2015). Similarly, Modeling International Relationships in Applied General Equilibrium (MIRAGE) covers 113 regions of the world and up to 57 sectors (IFPRI 2015). MIRAGE was used to analyze climate change impacts in South-Asia (Laborde et al. 2011). A version of MIRAGE called MIRAGE-BioF was used to analyze biofuel policies, as well as to assess the impacts of trade and agricultural policies on income and poverty in developing countries (Valin et al. 2013). While these represent global models, there are ongoing efforts to improve economy-wide models at individual country-levels. For example, under the Nexus Project, which is a loose consortium of organizations engaged in building and using CGE models for African countries, an effort is underway to improve and expand the scope of analysis. Data coverage is currently being expanded to cover energy and water sectors and the inclusion of biodiversity and ESS is under consideration.

Economy-wide models allow calculating the costs and benefits accrued to society in general from investments in conservation of agricultural biodiversity and ESS. These models can take into consideration the indirect impacts, such as loss to tourism, recreation, hunting and fishing, from agricultural run-off and leaching from fields many miles away. The models can also be used to examine potential impacts under various policy options to conserve or enhance biodiversity and ESS, on different sectors of the economy. As indicated in figure 5, given the scale at which these models operate, it is difficult to precisely link the estimated impact to specific crops, fields or local markets. But, if linked to analyses in other sectors and to analyses at lower scales, a given policy can be fully examined to consider the impacts on productivity, biodiversity and ESS with linkages to specific crops, fields, landscapes and markets.

5. Concluding remarks

This paper has presented a conceptual framework for integrating biodiversity and ESS into economic analysis of agricultural systems. As global food security is intrinsically linked with biodiversity and ESS, it is critical that any analysis of the productivity impact of a given agricultural technology also includes its environmental footprints. The impacts of how biodiversity is manipulated at the field level can ripple horizontally across landscapes and vertically across economic scales, requiring linkage in analyses across these scales. While the paper does not devote significant time to this issue, the paper also points out the need for temporal consideration in analysis since the cost of preserving biodiversity and ESS are privately borne in the short-run, but its gains are publicly accrued over a longer timeframe.

The paper also points out the need to examine ESS impacts of crop choice and agricultural practices and link these impacts back to yield impacts in the long-run. Yield predictions can then be incorporated into economic models at multiple scales to examine future implications for food security, through the impact on productivity, biodiversity and ESS. It is important to consider the analysis at multiple scales in order to more comprehensively capture intervention impacts. At the local scale, the profitability of a given innovation can be considered in the context of a farm enterprise or at the household level, with linkages constructed to ESS flows. At the agriculture sector level, the given innovation can be examined in the context of a range of agricultural commodities and their domestic and international markets. At the economy-wide level, the impact of a given innovation on ESS can take into consideration the effects beyond the agricultural sector. Therefore the analysis at each scale complements the analysis at another scale, indicating the need to have analyses linked across scales.

Given the current state of science regarding geospatial data, computing and modeling capabilities, it is feasible to regularly integrate biodiversity and ESS into analyses which are designed to assess the food and nutritional security impacts of a given agricultural innovation. However translating this idea into practice is more complex. As discussed by Antle et al. (2015) linking the relationships between land management decisions and multiple outcomes is complex and requires coordination across a number of different stakeholders. The authors point to the need for infrastructure to support the management of agricultural landscapes. While efforts have been made to establish platforms for sharing data and tools, more can be done in this area. As shared platforms for data, analytic modules, tools and models are essential for integrating biodiversity and ESS into economic analysis of agriculture systems, a question arises regarding who funds it. Funding agencies and the research community need to explore different options for incentivizing the sharing of data and computer models. Antle et al. (2015) present some suggestions, including the role for private-public partnerships, within the context of the United States. Food security of any given country is linked to actions and well-being of other countries. In the context of challenges presented by climate change and degradation of ESS globally, any infrastructure for data sharing and facilitating analysis in the United States should also be linked to global data and research efforts. To confront the global challenge of food security and climate change we need a global effort to perform analyses that allows identifying the best options to increase agricultural productivity, while also maximizing the global availability of macro and micro-nutrients and minimizing the environmental footprint of agriculture production systems.

While underscoring the need to perform the trade-off analyses discussed in this paper, it has to be noted that these models are merely approximating very complex systems. In some areas we have a good understanding of the relationships and in others only an emerging understanding. The type of analysis advocated here will have inherent weaknesses and will need to act in parallel with other types of evidence – some of which will be qualitative. However, developing these analytical approaches will likely help facilitate transdisciplinary working and systems thinking. It will expose some of the areas where we currently lack understanding – identifying new research priorities, which in turn will lead to improvements in analysis.

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