Literature Review on the Integration of Ecosystem Services in Agricultural Economic Models

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Abstract

The Millennium Development Goals (MDGs) will be replaced by Sustainable Development Goals (SDGs) in the latter half of 2015. The SDGs and the CGIAR's System Level Outcomes, as specified in its Strategy and Results Framework 2016–2025, both seek to reduce poverty, achieve food and nutritional security and, at the same time, maintain or enhance natural resources management and ecosystem services. Yet most of the analytic tools used in assessing potential gains from investments in agricultural research either fail to take into consideration the environmental impacts, including biodiversity or, if they do, it is at a very limited level. The CGIAR Research Programs (CRPs) for the Second Call (2017-2022) adopt a systems approach in implementation of its research programs and therefore require a fully integrated consideration of biodiversity and ecosystems services at all scales and all phases of any given agricultural system. Given this context, this document reviews existing methodologies and available data with the view of identifying how biodiversity and ecosystem services can be integrated into the analyses at multiple scales as required for a systems-level analysis; households, farms, landscapes, agriculture sector and economy-wide. The literature review is also designed to identify the possible synergies between models at different scales to enable a better understanding of the trade-offs between different agricultural systems and their environmental services provision, as well as its impact on human well-being and society in general.

Keywords: bio economic models, valuing ecosystem services, valuing biodiversity, geospatial analysis, modelling agricultural systems.

1. Introduction

The Millennium Development Goals (MDGs) will be replaced by Sustainable Development Goals (SDGs) after the UN Summit in September 2015. The SDGs and the CGIAR's System Level Outcomes, as specified in its Strategy and Results Framework 2016–2025, both seek to reduce poverty, achieve food and nutritional security and, at the same time, maintain or enhance natural resources management and ecosystem services (CGIAR 2015). Agricultural ecosystems supply the world's population with food, fibre and other harvestable goods (Garbach et al. 2014; Power 2010; MA 2005). At the same time, the functioning of these systems depends on ecosystems services (ESS) provided by natural ecosystems (Power 2010). According to a widely used definition brought forward by 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). Examples for ESS related to agricultural ecosystems include pollination, biological pest control, maintenance of soil structure and fertility, nutrient cycling and hydrological services (Power 2010). Here, biodiversity plays an important role in the provision of these services (MA 2005).

Yet, the continuing intensification of agricultural production, along with increasing urbanization and land degradation, threaten the provision of ecosystem services from, by, and to agricultural systems (Balbi et al. 2015; Robertson et al. 2014; Foley et al. 2005). According to Foley et al. (2005), approximately 40 percent of the Earth´s surface is covered by croplands and pasture. The MA report (MA 2005) mentions that around 60 percent of ecosystem services measured in the assessment were being degraded or unsustainably used as a consequence of agricultural management and other human activities. Furthermore, the expansion of modern agriculture, including livestock rearing, is a major driver of global environmental change, through impacts on land use, land cover, water balance, water quality, pollination, nutrient cycling, soil retention, carbon sequestration, climate regulation and biodiversity (Balbi et al. 2015; FAO 2007). Given the resource needs associated with current population growth and the growing middle classes, the negative environmental impacts may become further exacerbated with the anticipated increase in weather uncertainties related to climate change and declining or depleted natural resources available for food production. Such trends give reason for concern, particularly since populations may potentially increase by up to 9.6 billion by 2050 (United Nations 2013), consequentially food availability may have to expand by 60 percent globally and up to 100 percent in developing countries (FAO 2010).

Due to the linkage between global food security and many ESS, it is very important to understand their relationships and the trade-offs between them (Balbi et al. 2015). While investigating crop yield potential is important, it is also critical that we have a better understanding of the different factors affecting the food production system, such as biodiversity conservation, pollination, pest and disease control, water resources (quality and quantity), climate regulation, land degradation, air quality, land use for recreation, and consumer demand for diet diversity (Balbi et al. 2015). Since pursuing one specific objective in agricultural production, such as yield maximization, generates inefficient results when multiple ESS are considered, it is of particular importance to understand how different agricultural management practices impact natural capital stocks and thereby the provision of ESS (Foley et al. 2005). This requires the quantification of the different trade-offs between agricultural production and ESS (Balbi et al. 2015).

An important characteristic of ESS from an economic and political point of view is their public goods nature. This means that they exhibit neither rivalry nor excludability. Rivalry refers to whether one agent´s consumptions is at the expense of another´s consumption. Excludability refers to whether agents can be prevented from consuming (Perman, et al. 2009). For example, an aesthetic view is a pure public good. No matter how many people enjoy the view, others can also enjoy it. The problem with public goods is that although people value them, no one person has an incentive to pay to maintain the good. This entails the risk of a provision of ESS at levels below the social optimum. Thus, collective action is required to produce the most beneficial quantity.

ESS depend on the interaction of multiple ecosystem types at different temporal and spatial scales, characterized by dynamic and non-linear relationships (Birkhofer et al. 2015; Balbi et al. 2015; Bennett et al. 2009), and the production of ESS in agricultural systems depends on the services provided by neighbouring ecosystems (Power, 2010). Yet, analytical models which can integrate across these different scales, capture the complex behaviour of (agricultural) ecosystems, and evaluate agricultural systems at different scales, from farm level to global level, are scant. Statistical analysis can only partly describe the complex relationships (Sun and Müller 2013). Even simulation models, which take a more systems oriented approach, have often focused on isolated processes and rarely examined effects of agricultural practices in multiple ecosystems (Balbi et al. 2015; Barraquand and Martinet 2011).

In order to inform decision makers regarding resource allocation and planning, it is important that analytic tools and methodologies integrate ESS. Analysis and information presented to policy makers for consideration of appropriate policies to promote sustainable practices should be based on approaches that allow the integration of evaluation across different scales. Such approaches can consist of methodologies that can combine different models techniques (Balbi et al. 2015). A prerequisite for all approaches is the availability of necessary data, including spatially explicit quantitative and semi-quantitative data and expert opinion (Balbi et al. 2015).

Against this background, under the CGIAR Research Program on Policies, Institutions, and Markets (PIM), Bioversity International convened a workshop to identify opportunities to enhance existing agricultural modelling capabilities to incorporate key ecosystem services, which affect sustainable agricultural productivity growth, and to support these modelling capabilities with relevant geospatial data from Bioversity International and other sources. The ecosystem services that the workshop considered were associated risks of pest/disease incidence, pollination, water quality and use efficiency, and soil health. These ecosystem services are, in turn, affected by agricultural crop diversity and land use patterns.

The present literature review, on the Integration of Ecosystem Services in Agricultural Economic Models, has the following aims.

It is designed to provide an overview of models at different scales and the possible synergies between them that can contribute to a better understanding of the trade-offs between different agricultural systems and their environmental services provision, as well as its impact to human well-being and society in general. In particular, it is hoped that the literature review will be valuable in informing discussions on model enhancements to conduct trade-off analysis between increasing productivity, nutritional outcomes and environmental outcomes at different scales ranging from the household, farm, landscape and agricultural sector to economy-wide models. In Section 2, a basic conceptual framework is presented as a guideline for model based evaluation of ESS. Section 3 presents a review of economic agricultural models, including farm level, landscape, partial equilibrium and general equilibrium models. For each level, selected models are presented with a brief description of their assumptions, methodologies and an assessment of their strengths and weaknesses. Section 4 deals with requirements for spatial data for the model based assessment of biodiversity and ESS. Section 5 presents a summary of the report, highlighting key messages and gives recommendations for further work.
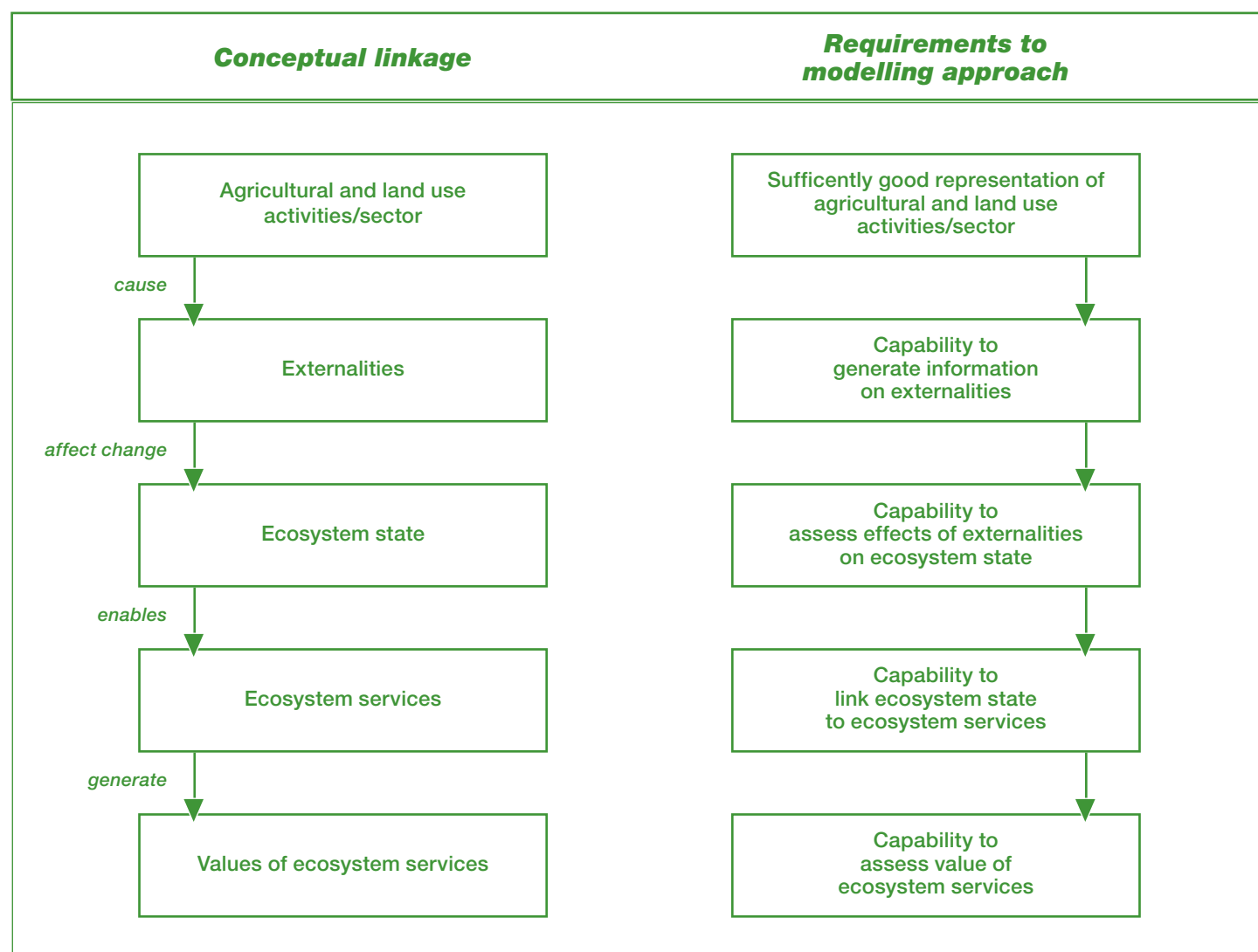
Figure 1: *Conceptual framework for the model based assessment of the value of ecosystem services.*

2. Conceptual Framework

As a basic conceptual framework for the review of the literature on model based evaluation of ecosystem services, we considered a simple chain of linkages between agricultural and land use activities or the agricultural sector respectively (depending on the scale of analysis), the value of ecosystem services and the trade-offs between them. In this chain, as represented in Figure 1 (left column), agricultural and land use activities cause externalities. Externalities affect the state of ecosystems, which provide ecosystem services. Human society eventually attaches a particular value to ecosystem services. Any changes to the state of ecosystems caused by externalities would also lead to a change in their ability to deliver ecosystem services and, consequently, in ecosystem value.

An example to illustrate this concept would be that agricultural activities cause externalities in the form of water pollution. Water pollution, in turn, affects water quality and thereby the state of aquatic ecosystems. This leads to changes in the capacity of the ecosystem to provide safe drinking water of fishing as ecosystem services and reduces their value. As a second example, agricultural intensification may lead to reductions in biodiversity and, consequently, negatively affect pollination or biological pest control (Power 2010).

A first contribution of this conceptual framework is that the elements of the chain that connect agricultural activities, or the agricultural sector as a whole with ecosystem services value, are clearly articulated. Doing so avoids the often encountered confusion between externalities, indicators of ecosystem state and ecosystem services. Secondly, the framework helps to formulate requirements of modelling approaches which are designed for evaluating ecosystems services as affected by agricultural and land use activities.

The requirements for a modelling approach to evaluate ecosystems services are illustrated in Figure 1 (right column Firstly, a sufficiently good representation of agricultural activities at the scale of interest (e.g. farm, region) is needed. 'Sufficiently good' thereby means that the model has to be able to describe system states and processes that cause externalities. For an analysis aimed at assessing trade-offs between ecosystem services and other functions of the food system, such as the provision of food and nutrition, it also means that a sufficiently comprehensive representation of agricultural production has to be provided. This includes both system elements and (dynamic) linkages to provide a picture of the (static) state of the system and how it changes in response to external driving forces. System elements can be translated into availability and quality of the data underlying the model. Linkages and model responses to external drivers translate into adequate behavioural assumptions.

Secondly, the model has to be capable of generating information related to externalities of interest. This implies that the set of elements and processes described should be sufficiently broad to capture these externalities, including relevant biophysical variables and sets of indicators. Also, linkages between agricultural production activities and externalities should be clearly spelled out and quantified.

For example, the amount of fertilizers, soil type, and weather conditions that lead to a certain crop yield, are also responsible for the externalities to be evaluated, such as leaching or nitrogen run-off. These linkages should be articulated by some functional relationships that provide quantitative input for the models. Once externalities are described and quantified, the approach has to be able to assess how the state of the ecosystem of interest is affected. This involves linking (changes in) indicators of externalities to (changes in) ecosystem states, i.e., a description of the ecosystem and its response to externalities. Thirdly, the approach needs the capability to link a given ecosystem state to quantifications of ecosystem services that are provided. It should be possible to map changes in ecosystem state into changes in ecosystem services. Finally, the approach has to be able to assign values to the ecosystem services of interest.

It has to be noted that not every element of the chain just described has to be explicitly represented in the modelling approach. Shortcuts are possible. Externalities can, for example, be directly linked to ecosystem services without providing an explicit description of the ecosystem state. Also, the assessment of the suitability of a given modelling approach for the evaluation of ecosystem services has to start from the end of the chain, i.e., by defining which ecosystem services are to be evaluated. The model used in a research depends, of course, on research purpose and it may not fully cover the entire spectrum of the agricultural system. However, when desired, it may be possible to conduct analysis at the full system level by exploiting the potential linkages across existing models at different scales.

The better a modelling approach fulfills the requirements just formulated, the better it is capable of assessing trade-offs and complementarities between food production, productivity, income and the environment. Departing from these requirements, we can spell out a number of specific questions that can be posed to facilitate the assessment of the suitability of a specific modelling approach and to provide a checklist that can guide a review of the literature on model based evaluation of ecosystem services:

- Is the representation of agricultural activities, or the agricultural sector, sufficiently good to provide information related to the food provision function of agriculture?
- Is the representation of agricultural activities, or the agricultural sector, sufficiently good to provide information on externalities that affect the ecosystem services of interest?
- Are the behavioural assumptions adequate to describe how external drivers affect the system?
- Does the model generate information on nutrition, productivity (income) and environment (externalities)?
- Is the approach capable of linking externalities to changes in ecosystem services?
- Does the approach provide an evaluation of ecosystem services?

3. Review of Agricultural Economic Models

To examine the trade-offs between productivity, nutrition and ESS, it is necessary to consider a set of analytic tools designed for different scales since the socio-ecological processes linked with food production, processing, delivery and consumption systems straddle across different horizontal and vertical levels of aggregation. Analysis, at the highest level of aggregation, can provide insights regarding the trade-offs at the national, macro level and indicate the cross sectoral impacts of any specific intervention designed to enhance productivity or ESS. Given the inter-sectoral linkages, the overall impact to the community or the economy is often greater than the sum of benefits accruing to targeted sectors (Kaimowitz and Angelsen 1998). However, as aggregated data are used for these analyses, such tools cannot capture the spatial details of ESS flows and their impacts along flow-pathways. Typically, analytic models found in agricultural economics literature are individual households, farms or firms, small land areas, regions, countries and the world. The first group of models reviewed in this report is household/farm level models. The second group covers landscape models. As a third group, partial and general equilibrium models are reviewed.

3.1. Household/Farm Modelling

Farm household models were originally designed as tools for price policy analysis. These models are appropriate for analyzing the empirical relationship between farmer´s land use patterns, household preferences and resource availability. These models are capable of incorporating considerable details regarding different crop and livestock systems and examining a number of different technologies and potential impacts of a range of policy interventions (Louhichi et al. 2010; Kaimowitz and Angelsen 1998). The models can be used for time period, or simulated for impacts over a number of years, i.e. for dynamic analysis.

These models have been employed in research ranging from adoption of technology, such as irrigation technology (Berger 2001), impact of population, market forces in agricultural extension (Angelsen 1999) to deforestation (Upadhyay et al. 2006). A few models have also incorporated environmental services in the analysis, including biodiversity (Balbi et al. 2015; Louhichi et al. 2009).

Household/Farm models are often applied to subsistence agriculture where production, labour allocation and consumption decisions are linked due to market imperfection (de Janvry et al. 1991). As far as the markets are perfect, households are indifferent to consuming own produced or market purchased goods. Thus, the model is separable and the optimization program can be solved recursively. However, if the market fails, the separable assumption does not hold and production and consumption decisions have to be solved simultaneously (Taylor and Adelman 2003).

Farm/household models require a considerable amount of detailed data. Additionally the results of the analysis may be applicable only to the case studied (Louhichi et al. 2010). Given the increasingly available open source data, the data constraints for household analysis may become less binding. Nevertheless, the challenge remains regarding the relevancy of results obtained from household analysis at larger levels of aggregation. For example, can the results be relevant for regional agricultural production systems? The use of remote sensing data to perform complementary analysis may provide some interesting possibilities to scale the results obtained from household models to larger geographies. Another challenge of these models, is in dealing with considerable model uncertainty (Troost and Berger 2014).

3.1.1. FSSIM (Farming System Simulator Model)

FSSIM is a static farm model which can be used to assess the impact of agricultural and environmental policies on the performance of farms and on indicators of sustainability (Louhichi et al. 2013). It consists of a data module on agriculture management (FSSIM-AM), together with a mathematical programming model (FSSIM-MP). FSSIM-AM can be used to identify current and alternative production activities and to quantify their input and output coefficients (such as yields and environmental effects) using the biophysical field model APES (Agricultural Production and Externalities Simulator). After the FSSIM-AM outputs have been generated, FSSIM-MP selects those that best fit the farmer´s behaviour, given the resources endowment and the technological and political constraints, to predict farmer responses to new technologies, as well as to policy and market changes (Louhichi et al. 2013).

FSSIM is generally used to forecast potential land use changes, production, input use, farm income and environmental externalities (e.g. nitrogen surplus, nitrate leaching, pesticide use, etc.). Model outputs may be used for other research or for informing decision makers. They can be further translated into indicators to measure the potential impact of a given policy intervention (Louhichi et al. 2013).

FSSIM model has an extension for developing countries called FSSIM-Dev (Farm system Simulator for Developing Countries). FSSIM-Dev is a non-linear optimization model which relies on the general household´s utility framework and the farms´ production techniques in a non-separable regime (Louhichi and Gomez 2014).

FSSIM model has been used to analyze agricultural and environmental policies in the European Union (Louhichi et al. 2010; Louhichi et al. 2009), trade liberalization (Louhichi et al. 2009) and food security and rural poverty alleviation in developing countries (Louhichi and Gomez 2014). FSSIM-Dev was employed to analyze rice support policy in Sierra Leone (Louhichi and Gomez 2014).

Strengths and Limitations

FSSIM model has a strong relevance in terms of conceptual and technical issues, such as generic and modular setup, and explicit representation of technology. The model gives a good representation of the agricultural activities. Moreover,

FSSIM model captures the following externalities; soil erosion, nitrogen leaching, water drainage, soil fertility rate, soil organic matter, pesticide volatilization, pesticide run-off, pesticide leaching, erosion peak, run-off peak, average farm nitrogen surplus, farm gate nitrogen efficiency, crop diversity (Louhichi et al. 2009).

Despite its strong relevance, the FSSIM model presents some limitations. One is the non-consideration of imperfect markets for factors of production such as labour, land and capital, which occur frequently in developing countries. Only market imperfections in goods are included (Louhichi and Gomez 2014). The model incorporates perennial crops in a relatively simple manner, as age structure of plantations, different costs and economic returns associated with the establishment period are not taken into account (Louhichi and Gomez 2014). It is a static model and is incapable of representing farmer behaviour with respect to production activities that are not observed during the reference period (Louhichi and Gomez 2014). Finally, forests are not included in the model.

Options for improvement

The model can be enhanced to improve the inclusion of auto-consumption and household labour use. Similarly, modifications can incorporate a dynamic function, thus allowing modellers to trace the long run trajectories of policies and indicators. FSSIM could incorporate other environmental services (ESS) in the agricultural systems such as biodiversity and pollination, as well as considering forests in the analysis.

Currently, FSSIM is being enhanced to allow investigation of the transition of impact analysis from farm to village/regional and national levels (Louhichi et al. 2013).

3.1.2. MPMAS (Mathematical Programming based Multi Agent Systems)

MPMAS is a simulation package for dynamic modelling of agricultural holdings. It is based on an agent based module representing the activity of land users with a cellular component representing a geographical landscape (Berger and Schreinemachers 2009). Through the interactions and inter-dependence of the agents with the landscape of the two components, both the agents and the landscape are integrated (Berger and Schreinemachers 2009).

MPMAS uses mathematical programming to model the production, investment and consumption decisions of farm agents. Agents in MPMAS maximize expected utility by choosing the optimal land use and resource allocation taking into account individual risk aversion. The software simulates multi-period dynamics by implementing the temporal carryover of agent's resources and updating agent expectations (Berger and Schreinemachers 2009).

MPMAS is designed such that it allows linkages with external crop growth models through crop yields, such as MONICA (Model for Nitrogen and Carbon in Agroecosystems) (Latynskiy et al. 2014) and TSCP (Tropical Soil Calculator Productivity) (Schreinemachers 2006). It can also be linked to models for measuring trace gas emissions from agricultural systems such as DNDC (DeNitrification – DeComposition) (Latynskiy et al. 2014), Expert-N (Troost et al. 2012).

Moreover, a study mentioned that this model could be coupled with a graphical user interface (GUI) containing soil maps and historical climate data from local meteorological stations as well as synchronization with Google Maps and display terrain and road maps from Google Maps (Latynskiy et al. 2014). The GUI provide visualized information on simulated optimal land use, crop yields, per hectare gross margins of different land use activities and total profit of farms.

This model has been used for analyzing agricultural innovations, such as the diffusion of new crops and high yielding varieties, greenhouse cultivation, and irrigation (Schreinemachers et al. 2010; Schreinemachers et al. 2009; Berger 2001). Other studies have examined market dynamics (Berger and Schreinemachers 2009), trade-offs between agri-environmental and clean energy climate change adaptation (Troost et al. 2015), water use efficiency (Arnold et al. 2015), environmental change (Quang et al. 2014; Grovermann et al. 2013), soil fertility (Schreinemachers et al. 2007), and the impact of policy intervention on farm households (Latynskiy et al. 2014). Research using this model has primarily focused on developing countries, such as Uganda, Chile, Ghana, Thailand, Vietnam, and Brazil. Some researchers have also used MPMAS for application in Germany.

Strengths and Limitations

The MPMAS framework is open-sourced and allows the integration of different factors influencing farm decision making, together with sub-models of biological and demographic processes in one simulation model. Therefore, the model gives a good representation of land use activities (e.g. crop rotation and inter-cropping activities are considered) and is capable of generating information on some externalities. Moreover, the model has the capacity to assess effects of externalities in the ecosystem and, in turn, their link to some ecosystem services. The model considers the development of agent and environment characteristics over time. This allows tracing the long run trajectories of selected indicators. Given its formulation, the model offers possibilities to scale site-specific analysis to larger geography and to scale up from farm to regional level.

On the other hand, the complexity of the model requires substantial time and effort to understand its functionality. The Mixed Integer Linear Programming (MILP) approach of modelling farm decision-making, demands parameterization of all possible decision alternatives. Therefore, a profound knowledge of the study area production system has to be obtained prior to model construction. Thus, a large amount of data and literature has to be searched and processed for setting up the model. Moreover, the model cannot capture all the processes that occur at higher levels.

Options for improvement

Currently, the MPMAS team is working to incorporate decisions under uncertainty (Troost and Berger 2014), as well as collective actions/cooperation between farmers. MPMAS could also explore incorporating more environmental services (ESS) in the agricultural systems such as biodiversity and pollination. Operating on an open source format and leveraging data, model-modules and knowledge from different open sourced resources provide huge potential for this type of modelling framework.

3.1.3. ARIES (Artificial Intelligence for Ecosystem Services)

The ARIES methodology aims to quantify ESS taking into account their dynamic complexity and consequences. For this purpose, the model employs a combination of ecology, economics and geography to support decision making (Villa et al. 2014). This methodology includes five key components:
i)   the ESS beneficiaries
ii) the service providing the ESS benefit expressed in physical units or relative rankings (e.g. kg of crop yield)
iii) the carrier of the benefit, which can be beneficial or detrimental to humans;
iv) the use of the carrier such as whether its use by one excludes the use by others
v)   the flow type used in routing the carrier from ecosystems to people or routing people to ecosystems (Balbi et al. 2015; Villa et al. 2014).

Each of the five components is set up using data and models according to research interest and are linked based on the direction of the flow carrier. These models can quantify and map source locations (ecosystems), sink locations (landscape features that can be degraded or can deplete a carrier), and use locations (human beneficiaries of the service), connecting these areas to quantify service flows. The implementation combines spatially explicit models of ESS provision and use with dynamic flow models for a description of the benefits through a certain landscape. The uncertainty associated with the decision making process is managed using spatial Bayesian networks (ARIES 2015; Balbi et al. 2015).

ARIES is used in different countries for different purposes, for example, ARIES is used to measure carbon sequestration in Madagascar, Mexico and USA, flood regulation and aesthetic view in USA, freshwater supply in Mexico and USA and sediment regulation in Madagascar, the Dominican Republic and the USA (ARIES 2015).

The use of ARIES in economic analysis appears to be new and is limited. Recently Balbi et al. (2015) attempted to capture and quantify ESS trade-offs in the crop systems of Llanada Alavesa in the Basque Country in Spain. They developed several sub-modules including one for agriculture production, which gives a description of the relationships between input variables and crop yields through a spatially explicit Bayesian model. A module also addressed climate regulation through the soil net carbon stock changes, direct soil net carbon stock changes, direct soil N_2O inputs and indirect emissions associated with the manufacturing of mineral fertilizers, and air quality through the NH_3 emissions. Water quality was considered in a module as a combination of indicators of nitrate leaching and phosphorus losses.

Strengths and Limitations

ARIES is an open-source resource and is able to work with a relatively limited amount of data. This data is generally accessible in the public domain. For instance, ARIES stores hundreds of pre-loaded local scale through more aggregated GIS datasets on the ARIES Geoserver. These data are annotated with relevant concepts, thus ESS models automatically call on, transform and integrate the relevant data into each model.

Furthermore, given the modular nature of the modelling approach, ARIES facilitates the integration of more analytic modules and data sets for detailed spatially explicit studies of ESS under different management practices and agricultural landscapes. For instance, in the work of Balbi et al. (2015), the modelling framework is able to carry out quantitative assessment of the synergies and trade-offs between different ESS as a consequence of management practices and climatic conditions.

Balbi et al. (2015) provide an example of the potential use of ARIES in trade-off analysis. Their own work was somewhat limited in scope and did not incorporate much complexity regarding agricultural practices, land use options and demand aspects of ESS.

Options for improvement

This model provides tremendous potential for linking ESS to bio-economic models for trade-off analysis between productivity, nutrition and ESS health. Its open-source platform is an added strength. ARIES can handle dynamic aspects of agricultural systems, and should be able to incorporate different ESS, including biodiversity, into the model.

3.2. Landscape Models

The landscape approach aims to contribute to sustainable development by supporting economic and social development combined with conservation efforts. An important element is the involvement of stakeholders from different concerned interest groups in decision making on land use. With this element, a land-use strategy may be developed that takes into account the objectives of each stakeholder group, as well as to minimize costs and maximize the benefits for each, while recognizing certain trade-offs (Horn and Meijer 2015). For example, forest conservation could have many benefits for various stakeholders, but might be cost ineffective for direct forest managers. Therefore, sharing costs and benefits more equally among stakeholders could make this activity economically more interesting for all participants. In order to reach such level of cooperation, local stakeholders need to be aware of the economic and non-economic values of forests that could

enhance local livelihoods. Out of necessity, a landscape modelling approach has been developed to focus not only on sustainable forestry but also on other issues such as poverty alleviation, education and sustainability of supply chains (CIFOR 2012). Moreover, large scale landscape approaches could enhance the field level benefits on biodiversity or climate mitigation efforts (Horn and Meijer 2015).

Given the scope for analyzing multiple benefits and costs, spatially explicit ESS provision modelling tools have become increasingly available. These tools describe multiple service supplies and different function interactions. These models are able to assess the impact of human activities on the provision and value of multiple services in space and time. However, these models do not yet explicitly simulate spatial and temporal feedbacks in service supply as a result of dynamics in service demand (F. Müller et al. 2010). Another disadvantage of these models is that they often ignore economic aspects (demand and supply interactions) in their scenario analysis. For that reason, they are best suited for use in combination with economic models. Spatial models have high data requirements and limited spatial coverage, where sometimes higher aggregation processes are not captured (Smeets et al. 2014).

3.2.1. Farm and Landscape IMAGES Model

Landscape IMAGES is a spatially explicit, GIS based land-use optimization methodology which employs the Differential Evolution Optimization Strategy and the concepts of Pareto optimality. This approach combines agronomic, economic and environmental indicators with biodiversity and landscape quality indicators (Groot et al. 2007). The model assesses the contribution of farm management and other landscape elements to economic and environmental performance criteria. Activities on two or more spatial units may interact with respect to the performance criteria (Groot et al. 2009). Therefore, different spatial configurations of activities result in different values of the performance criteria. The exploration of the trade-offs between performance criteria or objectives, such as gross margin, nature value, landscape identity and environmental quality indicators, is formulated as a multi-objective design problem (Groot et al. 2009; Groot et al. 2007). For this purpose, multi-objective optimization algorithms are employed to produce maps of alternative allocations of farming activities to fields. The results are used as an input for discussions among farmers, landscape management organizations and other stakeholders (Groot et al. 2010; Groot et al. 2009; Groot et al. 2007).

This model has been used to study interactions between various ESS, such as connectivity of vegetation structure (hedgerow) for animal species dispersal (Groot et al. 2007), soil fertility (Groot et al. 2007), loss of nutrients (Groot et al. 2007) and plant species prevalence (Groot et al. 2009).

Strengths and Limitations

The Landscape IMAGES model covers a large range of possible configurations of the landscape in terms of land-use, which means that farming activities can be constrained at field, farm and landscape scale and functions may be assessed at any combination of scales (Groot et al. 2009; Groot et al. 2007). These characteristics support the introduction of heterogeneity and diversity in a bio-physical environment, socio-institutional conditions and the resulting land-use or farming activity allocation (Groot et al. 2009). Therefore, the complexity of farming systems, as well as some of the externalities generated by different farm management options, can be well represented in the model.

Moreover, Landscape IMAGES gives the opportunity to explore different possibilities of multi-functional farming activities and landscape management by creating static images of potential futures which, in turn, can be used in multi-stakeholder discussions and decision making process (Groot et al. 2010). Carmona-Torres et al. (2011) mentioned that this framework can contribute toward identifying financial compensation arrangements for collective action among farmers.

On the other hand, results of the model have not been validated at the whole landscape level. Landscape parameters used in the model were selected based on input by landscape experts with research and regional background. Other model parameter were based on previous studies (Groot et al. 2010). The model is static and it assumes constant prices of inputs and outputs.

Options for improvement

This model is a useful tool for stakeholder's discussions, but a validation for the whole landscape system will be helpful. Although Landscape IMAGES would be suitable in the context of policy development, since it produces static pictures of potential future landscapes, an incorporation of dynamic trajectories would be desirable.

3.2.2. InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs)

InVEST is a spatially explicit, free and open-source software which estimates the biophysical provision of multiple ecosystem services across a landscape. InVEST provides maps of service use (who and where people are benefiting from service provision) and monetary value (the value that people receive from the use of service). Thereby the trend in service provision and values on the landscape can be predicted. A relative index of habitat quality (terrestrial only) is also provided as an indicator of the status of biodiversity, but it is not assigned an economic value (InVEST 2015; MacKenzie et al. 2012; Nelson and Daily 2010).

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[0]   *Pareto optimality is a state of allocation of resources in which it is not possible to make one or more persons better off without making at least one person worse off (Perman et al. 2003). In this model, the Pareto optimal solution set is a collection of alternatives that cannot be improved for one of the objectives without compromising any of the other objectives involved (Groot and Rossing 2011).*

InVEST determines ecosystem service provision and value on the landscape by using ecological and economic production functions (Tallis et al. 2012). Here, land-use, land-change, management and biophysical data on the landscape are inputs (Nelson and Daily 2010). Due to the scarcity of data, InVEST offers relatively simple models with few input requirements. These models are suited for identifying patterns in the provision and evaluation of ecosystem services. With calibration, these models can also provide useful estimates of the magnitude and value of services (MacKenzie et al. 2012). Current models are biodiversity, water quality, potential soil conservation, water quantity, carbon sequestration, pollination, managed forestry and non-timber forest product production, agricultural production, housing (property) values, cultural and spiritual values, recreation and tourism (Nelson et al. 2009). The Nature Capital Project is developing more complex, data intensive models (MacKenzie et al. 2012). InVEST is able to run at different complexity levels, which make this approach sensitive to data availability and comprehension of system dynamics. Results can be reported in either biophysical or monetary terms depending upon the needs of decision makers and availability of data (Nelson et al. 2009).

The software has been applied in many countries for different purposes. In the USA, InVEST was employed to evaluate carbon storage, water quality improvement for terrestrial species, timber production and outdoor recreation (Kovacs et al. 2012). InVEST is being used to create maps of priority areas for environmental conservation in China and Indonesia. In Colombia and Ecuador, the approach is used to design self-sustaining water funds for watershed protection. In the state of Hawaii, InVEST is used for providing recommendations about land-based carbon sequestration investments with other ecosystem service co-benefits (Nelson et al. 2010). In cooperation with the World Wild Fund (WWF) through the Natural Capital Project, InVEST was used in Indonesia to map the distribution and economic value of ecosystem services in priority watersheds. In Tanzania, InVEST was employed to map and value the ESS of mountains, with the aim of identifying areas that could be candidates for payment under REDD+ and voluntary carbon projects. (WWF 2015).

Strengths and Limitations

InVEST is an open-source software which covers a wide range of ESS, showing the value and the future flow of ESS on the landscapes and sea. Information on the current flow of ESS can demonstrate the contributions that ecosystems make, stimulating policy discussions about links between environmental and development objectives. Thus, InVEST is a useful tool for an active involvement of stakeholders. In an online survey conducted by Nemec and Raudsepp-Hearne (2012), survey respondents mentioned that InVEST was easy to use, simple, and had a good selection of important ESS, peer-reviewed methodology.

Moreover, InVEST can identify providers and beneficiaries of ESS and the magnitude of the benefits they currently receive, thereby helping to scope the feasibility

and design of new policy and financial mechanisms that create incentives for conservation, but information on the current flow of ecosystem services has some limitations. Firstly, it is a static snapshot of what is happening today, whereas policy-making involves looking forward to improve outcomes over time. Secondly, information solely about the current situation is not comparative; there is no consideration of alternatives. Since decisions often involve choices among many possible interventions, decision-makers need information on the results of their actions to show the trade-offs of each choice (MacKenzie et al. 2012). Moreover, the quality of output depends on the suitability of the included methods to address the study area and the quality and appropriateness of available data (Smeets et al. 2014). In the online survey conducted by Nemec and Raudsepp-Hearne (2012), limitations of InVEST identified by survey respondents included the modelling capabilities of freshwater services, the biodiversity model and the potential for over simplification.

Options for improvement

InVEST is a powerful open-source tool for ESS analyses which, in combination with other economic models, may provide very effective analyses. Moreover, an inclusion of dynamics in the model could improve its applications for policy purposes.

3.3 Partial Equilibrium Models (PE)

Partial Equilibrium (PE) models refer to quantitative methods which take into consideration only a part of the economy, assuming the rest of the economy remains unchanged (ceteris-paribus condition) (IDB 2015). Therefore, PE models only take into consideration a particular sector or market of an economy and ignore interactions with other sectors. This implies the assumption that the sector in question is small and therefore has little (if any) impact on other sectors of the economy (IDB 2015). PE models incorporate both supply and demand of the industry or sector of interest, hence being able to capture market equilibrium processes. PE models are widely used for agricultural sector modelling because they offer the possibility of a comparatively detailed depiction of the sector (as compared to economy-wide general equilibrium models) 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.

However, these models do not capture economic feedbacks between the agricultural sector and the rest of the economy. Its aggregate spatial scale has limited representation and linkages with externalities and ESS. Considering the importance of ESS, and maintaining crop genetic diversity for sustainability in agricultural production, these models can explore the incorporation of crop biodiversity in its design.

3.3.1. IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade)

IMPACT is a global multi-market, dynamic partial equilibrium model of the agricultural sector that provides long-term projections (up to 2050) of global food supply, demand, trade, prices and food security (Flachsbarth et al. 2015; Robinson 2014; Rosegrant 2012). The model covers 58 agricultural commodities, including cereals, soybeans, roots and tubers, meats, milk, eggs, oils, meals, vegetables, fruits, sugar and sweeteners and other foods. Livestock is included, as well as 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. Agricultural supply is represented by isoelastic yield and area functions at the FPU level. Yields and area respond to changes in own and cross prices, input prices and exogenous productivity and area shifters. Food demand is modelled with isoleastic demand functions at the level of 159 political regions, taking into account own and cross prices as well as changes in income and population. Dietary changes are taken into account by adjusting parameters to accommodate the gradual shifts in demand from staples to higher value commodities. This assumption is based on expected economic growth, urbanization and continued commercialization of the agricultural sector. The regions in the model are linked through international trade using a net trade modelling approach. World agricultural commodity prices are determined annually at levels that clear international markets.

IMPACT includes a water module which generates information on water availability for agriculture at the water basin level and which provides input for yield adjustments due to water related crop stress. Crop models of the Decision Support System for Agrotechnology Transfer (DSSAT) can be used to calculate yield shifters to assess climate change or technology impacts (Robinson 2014; Rosegrant 2012).

IMPACT model has been used to forecast future food needs under a number of different scenarios (Rosegrant and Cline 2003), biofuels (Rosegrant et al. 2008) such as with trade liberalization and climate change impacts on agriculture (Flachsbarth et al. 2015; Nelson et al. 2010; ADB and IFPRI 2009).

Strengths and Limitations

The model is versatile and can be used to analyze the impacts of different market drivers on the agricultural sector, such as trade liberalization (Flachsbarth et al. 2015). Moreover, IMPACT integrates inter-linked components, such as changes in climate, hydrology, water resources, crop productivity and food demand and security at the sub-regional, regional and global level (Flachsbarth et al. 2015; Rosegrant 2012). Among its advantages are comprehensiveness of regional and commodity coverage and the capability of capturing cross-commodity and inter-regional market linkages and feedbacks.

IMPACT is linked with different global climate models through the Decision Support System for Agrotechnology Transfer (DSSAT) and can take into account crop yield effects of climate change (Flachsbarth et al. 2015). In addition, the model provides information about hydrological fluxes and accounts for production effects of water stress. Future water demand and supply are endogenous, which is useful for calculating water footprints of agricultural production and identifying water scarcity hotspots under alternative production systems. IMPACT results can be linked with the Soil and Water Assessment Tool (SWAT) to measure impacts of expanded or intensified agricultural activity on the hydrological environment, through quantifying variations of nitrogen-based pollutants over time.

While Flachsbarth et al. (2015) employed the endemic bird´s risk of extinction and endangerment (expressed as an index %) to analyze the impact of different scenarios on biodiversity, IMPACT has not yet examined how cropping diversity in agricultural production may affect sustainable food production. It is possible that this can be explored for future model enhancement.

IMPACT's shortcoming is that it has relatively coarse spatial resolution. For instance, the model is aggregated globally in 256 spatial units and, in the case of Latin America, it considers 31 regions. Additionally, given its focus on a single sector, inter-sectoral linkages cannot be fully explored by IMPACT. These limitations preclude a comprehensive representation of different land use activities which makes it difficult to capture externalities and link these to biodiversity and ecosystem services.

Given its coarse spatial resolution, the model might also underestimate water scarcity in some areas of large river basins. In case of changes in livestock numbers, the model does not feed back into water supply and demand module.

As production costs are not explicitly included in the model, the model can predict future yields but it does not provide any indication of future productivity growth in terms of per unit of total production costs. In other words, profitability associated with different model scenarios is not captured.

Furthermore, IMPACT does not provide information on land-use transitions and dynamics. The link between agricultural and pasture expansion and deforestation is not always straightforward and its representation in IMPACT rests on simplifying assumptions. It is also assumed that newly abandoned agricultural areas are able to restore their carbon stock and biodiversity back to their original values (Flachsbarth et al. 2015). The carbon stock losses and adverse biodiversity impacts might not be fully reversible. This assumption could lead to an overestimation of the positive environmental impacts of reforestation.

Finally, forests are not taken into account in IMPACT but forests play an important role in the provision of ecosystem services. Consequently, the ability of forests to provide ecosystem services, pollination, pest control, disease incidence, and soil and water quality, cannot be analyzed with IMPACT.

Options for improvement

Future model enhancements can consider increased spatial resolution, better articulation of dynamic transitions in land-use changes, and inclusion of a forest module. As cost of production is not included explicitly in the model, it is advisable that profitability of different simulation scenarios be discussed when presenting and discussing the model results.

3.3.2. GLOBIOM (Global Biosphere Management Model)

GLOBIOM is a Global Recursive Dynamic Partial Equilibrium model that integrates the agricultural, bioenergy and forestry sectors. GLOBIOM has the aim of providing policy analysis on global issues relating to land use competition between the major land-based production sectors. The supply side of the model is built 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 up to five arc-minutes. Agricultural production is represented in a spatially explicit manner, with the capability of differentiating land use and production technologies, including cost of production at a level of >200,000 simulation units (Havlík et al. 2014; Havlík et al. 2011). Production adjusts towards the most cost efficient production mix which can satisfy demand at the level of 30 economic regions. Bilateral international trade is modelled with a spatial equilibrium approach, where individual regions trade with each other based on a criterion of cost competitiveness. Market equilibrium is determined through mathematical optimization which allocates land and other resources to maximize consumer and producer surplus. Prices are endogenous and the model is solved using linear programming simplex solver and can be run with the GAMS software (Havlík et al. 2014).

The model covers the 18 globally most important crops, a range of livestock production activities, and forestry commodities, as well as different bio-energy transformation pathways. Crops included in GLOBIOM represent more than 70 percent of the total harvested area and 85 percent of total vegetal calorie supply. Each crop can be produced under different management systems, depending on their relative profitability; subsistence, low input rainfed, high input rainfed and high input irrigated (Havlík et al. 2014). For each management system, crop yields and input requirements are calculated at the simulation unit level using the EPIC model (EPIC, 2015). As a land-use model, GLOBIOM simulates competition for land between different uses, driven by price and productivity changes.

The model has been employed for the analysis of impacts of climate change (Nelson et al. 2014), climate change mitigation (Havlík et al. 2014; Cohn et al. 2014; Reisinger et al. 2012), land-use change (Smith et al. 2010), land-use changes and biofuels (Kraxner et al. 2013; Mosnier et al. 2013; Havlík et al. 2011), schemes for reducing emissions from deforestation (REDD) (Mosnier et al. 2014; Mosnier et al. 2012), climate change mitigation and biodiversity (Frank et al. 2013), as well as livestock production and land-use change (Havlík et al. 2013).

Strengths and Limitations

The model provides detailed information on agriculture (including the livestock sector), forestry and bioenergy with a comprehensive spatial (i.e. global) and commodity coverage. It offers great detail at a grid cell level, providing a good representation of land use activities, including different crop and livestock management systems with their different productivities and input use requirements. It is capable of generating information on externalities from agricultural production, such as water use and GHG emissions.

GLOBIOM is a geographically explicit model with a high spatial resolution. The detailed representation of land-use covering the agricultural, forestry and bioenergy sector allows for providing information on land-use transitions and dynamics. This carries the potential of generating information relevant for the analysis of impacts of land-use change on biodiversity and ecosystems services. Land conversion possibilities can be allocated into the grid cells, taking into account suitability and protected areas. Moreover, it is one of the few models that consider forestry as an important component.

The detailed representation of agricultural production technologies, including a spatially heterogeneous depiction of crop and animal productivities, allows incorporation of feedbacks on changes in biodiversity and ESS on yields. This offers an option to evaluate the value of ESS.

The already streamlined incorporation of geospatial datasets into GLOBIOM offers the potential to easily link the model to newly available datasets of biodiversity and ecosystems services.

While offering a detailed representation of the land-use sector as a PE model, GLOBIOM is not capable of capturing economic feedbacks between the agricultural sector and the rest of the economy. This may become relevant in settings where the agricultural sector is a large part of the economy (i.e. developing countries) and where the focus of the analysis is on the demand side (e.g. because of the neglect of income effects on household demand).

While GLOBIOM generates information on externalities from agriculture and forest production activities, as well as from land-use changes, these may not comprise all externalities that are relevant for the assessment of biodiversity and ecosystems services.

Options for improvement

The model can explore incorporating information on externalities that are relevant for the assessment of biodiversity and ESS.

The possibilities to link the model with additional geospatial datasets on biodiversity and ecosystems services can be considered. The potential to develop the means for incorporating detailed yield effects of changes in ESS can,

in particular, be pursued. The EPIC model already in use for the parameterization of the crop production technologies or external tools may be used for this purpose.

3.3.3. MAgPIE (Model of Agricultural Production and its Impact on the Environment)

MAgPIE is a global, spatially explicit, recursive dynamic economic land-use model. It links regional economic conditions (e.g. agricultural commodities, technological development and production costs) with grid based biophysical constraints simulated by the dynamic vegetation and hydrology model LPJmL (Lotze-Campen et al. 2008). The model covers 10 regions worldwide and it has a spatial resolution of 0.5°x0.5°, resulting in around 60,000 grid cells. The model derives specific land use patterns and yields of agricultural production for each grid cell. MAgPIE makes a distinction between the different land types; cropland, pasture, forest and other land (e.g. non forest natural vegetation, present and future abandoned land, desert) but, unlike the cropland sector, the areas in the pasture and forestry sectors are fixed at their initial value in the study (Klein et al. 2014).

The objective function of the model is to minimize total cost of production for a given amount of regional food and bioenergy demand. Food and bioenergy for the 10 demand categories can be produced by 20 cropping activities and three livestock activities. Future trends in food demand are derived from a cross country regression analysis, based on future scenarios on GDP and population growth (PIK 2015 a and b; Lotze-Campen et al. 2008).

Trade in food products between regions is simulated endogenously, constrained by minimum self-sufficiency ratios for each region. This means that some minimum level of domestic demand has to be produced within the region, while the rest can be allocated to other regions according to comparative advantages (Popp et al. 2010). Costs of production are derived from the Global Trade Analysis Project (GTAP) Database. The model is implemented in the algebraic modelling language GAMS and the programming language R (Biewald et al. 2014)

For projections the model runs on a time step of 10 years. The link between two consecutive periods is established through the land-use patterns. The optimized land-use pattern from one period is taken as the initial land constraint in the next. If necessary, additional land from non-agricultural areas can be converted into cropland at additional costs (PIK 2015b).

The model has been used for the analysis of trade-offs between bioenergy, afforestation and food production (Humpenöder et al. 2014). Other studies have examined the link between land protection regimes and reduced deforestation (Popp et al. 2014); incremental changes in agricultural productivity, climate change mitigation and bioenergy (Popp et al. 2011); land-use, water consumption and bioenergy (Bonsch et al. 2014; Klein et al. 2014; Popp et al. 2011; Lotze-Campen et al. 2010); trade and blue water (Biewald et al. 2014); and food consumption (Popp et al. 2010; Lotze-Campen et al. 2008).

Strengths and Limitations

The model provides a good representation of different agricultural management options, including a representation of endogenous technological changes. Regarding ESS, potential outputs of LPJml/MAgPIE model are carbon storage in vegetation, carbon in soils and crop residue, annual transpiration (climate regulation), foliar protective cover and regulation of water flows.

On the other hand, MAgPIE does not capture much information on forest dynamics, thus limiting its scope of integrating change in ecosystem services (ESS). The LPJml model requires a high quality gridded global climate input, which is not often available.

Options for improvement

The biodiversity observation network (GEO BON) had initiated action to integrate LPJmL/MAgPIE with InVEST for the monitoring of environmental services. Data limitations present challenges for using these models in a monitoring context (Tallis et al. 2012).

3.3.4. CAPRI (Common Agricultural Policy Regionalized Impact Modelling System)

The CAPRI model is a Partial Equilibrium (PE) model with a focus on Europe (disaggregated in 280 regions, potentially disaggregated in 2000 farm types), but embedded in a global market model to represent bilateral trade between 44 trade regions (countries or country aggregates). It is designed to analyze the Common Agricultural Policy (CAP) and trade policies for agricultural products (Britz and Witzke 2014; M´barek et al. 2012). CAPRI was built to analyze a wide range of policies and topics related to the agricultural sector, including agri-environmental interactions (M´barek et al. 2012).

CAPRI consists of two modules; (i) a detailed and disaggregated supply module for Europe and (ii) a global market module. Both modules are linked by sequential calibration such that production, demand, trade and prices can be simulated simultaneously and interactively from global to regional and farm type scale (Britz and Witzke 2014).

The CAPRI data base uses many types of data sources, especially data from EUROSTAT, FAOSTAT, OECD and the Farm Accounting Data Network (FADN). The model has specific modules, which assure that the data used in CAPRI are mutually compatible and complete in time and space. The model covers about 50 agricultural primary and processed products from EU, from farm type to global scale, including input and output coefficients (Britz and Witzke 2014).

CAPRI allows simulating different scenarios and assessing different agricultural and environmental policies affecting agriculture, and has the capability of mapping the environmental impact. CAPRI was employed in several studies and projects related to EU and global agriculture such as the 2003 CAP reform (Britz and Witzke 2014; M´barek et al. 2012), the 2008 health check (Britz et al. 2012), introducing biodiversity targeted ecological focus area in the EU (Pelikan, et al. 2015), climate change effects

on EU agriculture (Shrestha et al. 2013), biogas production (Britz and Delzeit 2013) and livestock sector (Weiss and Leip 2012).

Strengths and Limitations

CAPRI gives detailed information on the agricultural sector, with an excellent representation of land use activities. The model is capable of generating information on externalities from agricultural production, such as water use and GHG emissions. Moreover, the model assesses biodiversity impacts through some biodiversity indicators which are included in the post-model calculation matrix (de Vries 2009).

The central limitation of CAPRI is that it is focused on the EU only. Hence, its usability for global analyses or analyses focused on tropical and subtropical regions is limited. Due to its rich representation of externalities and ESS, however, it can serve as a source of inspiration for the improvement of other models.

3.4. CGE (General Equilibrium Model) / IAM (Integrated Assessment Model)

A Computable General Equilibrium (CGE) model is a model covering production, consumption, intra-sectoral input and trade of all economic sectors for one country, a region or even all countries worldwide (M'barek et al. 2012). CGE models represent the optimizing behaviour of all agents within the economy as producers, consumers, factor suppliers, exporters, importers, taxpayers, savers, investors, or government. In this comprehensive coverage of economic processes lies the principal advantage of the approach.

Important uncertainties and limitations to CGE modelling 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. CGE models also tend to offer little detail in the representation of specific sectors, such as agriculture. This embraces that the representation of specific commodities or agricultural technology and technological change is usually limited. However, advances in bioenergy have been made in some GTAP model versions (Smeets et al. 2014), as well as assessment of ecosystem services and biodiversity using CGE ICES (Intertemporal Computable Equilibrium System) model (Bosello et al. 2011).

Integrated Assessment Models (IAMs) describe processes in the interaction of human development and the natural environment. IAM methods and tools draw on functional relationships between activities, such as provision of food, water and energy, and the associated impacts. These models were traditionally focused on climate change and air pollution. In the last few years, these models have been used to assess other impacts, such as over exploitation of renewable resources (e.g. forests), water scarcity, depletion of non-renewable resources (e.g. phosphorus) and air and water quality. IAMs could provide insights into how driving factors induce a range of impacts, taking into consideration

some of the key feedback and feed-forward mechanisms. IAMs need to be sufficiently detailed in order to effectively examine a given problem (de Vries 2009).

3.4.1. GTAP (Global Trade Analysis Project)

GTAP (Global Trade Analysis Project) is a global network of researchers and policy makers conducting quantitative analysis of international policy issues. With the goal of improving the quality of quantitative analysis of global economic issues within an economy-wide framework, GTAP provides both a global database of trade, production, consumption of intermediate use of commodities and services and a CGE model, known as the standard GTAP model (GTAP 2015).

The standard GTAP model is a static multi-region, multi-sector, computable general equilibrium model, with perfect competition and constant returns to scale. The model includes bilateral trade which is modelled following the Armington approach. The level of aggregation of the model, i.e., the number of regions and sectors represented, depends on the version of the database and the aggregation chosen by the model user for specific simulations (M'barek et al. 2012). The most recent version (8) of the GTAP database contains 57 commodities and 129 regions. The agricultural sector in GTAP database V8 is represented by almost 12 products on the production side and seven commodities on the demand side. The forestry sector is included through a forest products commodity (GTAP 2015).

Beside the standard GTAP model, several model variants or derivatives exist. Examples include GTAP-AEZ (Hertel et al. 2008), which adds a more detailed treatment to land heterogeneity and land endowments, or MAGNET, which amends the standard model with, for example, land supply curves, biofuels, or a routine to calculate average nutrition indicators. MAGNET covers 134 regions and 63 products (MAGNET 2015).

Strengths and Limitations

The principal strength of GTAP lies, as with other CGE models, in its comprehensive coverage of all sectors of the global economy. This enables market level feedbacks to be captured across sectors and regions. Capturing intersectoral linkages may be of particular importance in developing countries, where the agricultural sector is large and where factor market feedbacks (e.g. the labour market) matter. Limitations are the high level of aggregation in around 130 regions. The consequently rough depiction of agricultural production and the lack of capability to capture land-use change the dynamics, thus constraining the possibilities of generating insights in externalities and ESS which go beyond general statements at the national level.

Options for improvement

Even at the national level, GTAP has the scope to better integrate biodiversity and ESS into its analysis. The GTAP database and probably the GTAP model (or variants thereof)

can provide an overarching framework to ensure consistency in other more detailed scale of analyses conducted using other models.

3.4.2. MIRAGE (Modelling International Relationships in Applied General Equilibrium)

The MIRAGE model is a global, computable general equilibrium model (CGE) that has been developed to study trade policy scenario. The model has been used to assess bilateral and multilateral agreements (IFPRI 2015; Valin et al. 2013). MIRAGE supplies a rich set of indicators for each region that permits the measurement of policy impacts. These indicators include; changes in production, production factor uses, real wages, value added by sector, real GDP, real income, exports, imports, and terms of trade (IFPRI 2015).

MIRAGE can be used under different assumptions such as perfect or imperfect competition and dynamic or static approach. The GTAP database is its main source of information and MIRAGE covers 113 regions of the world and up to 57 sectors. In addition, it has been developed in parallel with the MAcMAp-HS6 database that allows detailed trade policy scenario consideration. When the dynamic features are used, a realistic baseline is built based on United Nations Agencies demographic projection as well as IMF economic growth assumptions (IFPRI 2015).

Production and consumption in countries are decomposed in regions through input-output tables, which are integrated in Social Accounting Matrix (SAM). Price transmission flows throughout regions and sectors are represented with associated prices. On the supply side, the production function in each sector is a Leontief function of value added and intermediate inputs, and factors of production (labour, unskilled and skilled; capital, land and natural resources). Factor endowments are fully employed. The only factor whose supply is constant is natural resources (IFPRI 2015; Laborde et al. 2011).

MIRAGE was used to analyze climate change impacts in South Asia (Labourde et al. 2011). A version of MIRAGE called MIRAGE-BioF was used to analyze biofuel policies, as well as to assess trade policy impacts and impacts of agricultural policies on income and poverty in developing countries (Valin et al. 2013).

Strengths and Limitations

MIRAGE provides a complete economy-wide perspective. It can assess how introduction of policies contribute to changes in production, consumption, prices and welfare across sectors and regions. The linkage to land-use allows consideration of different policy implications affecting agriculture. Trade policies can be modelled in considerable detail and various model extensions can be considered for the agricultural sector, for example in irrigation and climate change effects.

However, MIRAGE has limited use if the sector(s) are small, which provides no general equilibrium feedback effects. The model has limited flexibility to confront non-existing or virtual technologies, as well as difficulty in explicitly representing bio-physical balance on the supply side (soil nutrient, waste management, etc) (Smeets et al. 2014).

Options for improvement

MIRAGE could incorporate other environmental services (ESS) into its analysis.

3.4.3. IMAGE Model (Integrated Model to Assess the Global Environment)

IMAGE is a global model that integrates human and natural systems interactions. IMAGE covers 26 world regions. Land-use and land-use changes are presented on a grid of 5x5, while the processes for plant growth, carbon and water cycles are modelled on a 30x30 minutes resolution (Stehfest et al. 2014; Schaldach and Priess 2008). The model covers a wide range of themes; ecosystem services, demography, world economy, agriculture, energy supply and demand, emissions, land allocation, carbon, nitrogen and water cycle, climate change, land degradation (Stehfest et al. 2014). Drivers are population projections (from UN, IIASA, or from the PHOENIX model), economic drivers (from POLE Star), technological development, policy options and climate change. IMAGE uses input from Phoenix (demography) and has been linked to several other socio-economic models in global assessments, e.g. GTAP, Env-Linkages, WaterGAP, IMPACT. GLOBIO uses IMAGE output for the calculation of a biodiversity index (Stehfest et al. 2014; de Vries 2009).

IMAGE has been used to assess biodiversity (Alkemade et al. 2009) and ecosystem services, including soil erosion, pollination, pest control, and flood protection among others (Schulp et al. 2012). It has also been used to calculate land use emissions (Strengers et al. 2004), impacts of land use change on ecosystems and the environment on global scale (Eickhout et al. 2006; Leemans and Eickhout 2004; GEO 2002). IMAGE generates land cover maps which can serve as inputs for different types of studies such as bio-energy potentials (de Vries et al. 2007; Hoogwijk et al. 2005), impacts on land-use change on the carbon balance of the terrestrial biosphere (Müller et al. 2007).

Strengths and Limitations

IMAGE allows integrated assessments, enabling linkages and feedbacks at the global level and over different time periods. On the other hand, as it is a collection of many different sub-models, it can be time consuming to use as it is developed and operated by many people.

4 Spatial Data

The use of remote sensing provides information on the state and drivers of change on biodiversity and ecosystem services at multiple spatial and temporal scales. Many researchers stress the potential for synergies between remote sensing science and ecological research (Pettorelli et al. 2014; Burkhard et al. 2013; Ghazoul et al. 2010; Turner et al. 2004). The use of remote sensing technologies to support scientific research and conservation has increased over the last decade, making it an important tool for mapping and assessing the provision of ESS in different contexts (Pettorelli et al. 2014; Nemec and Raudsepp-Hearne 2012; Wulder et al. 2004). Remote sensing provides information for visualizing spatial and temporal patterns, as well as changes in ESS within a landscape (Paudyal et al. 2015; Baral et al. 2014; Nemec and Raudsepp-Hearne 2012). This information is helpful for estimating the potential impacts of a project on land use changes or management on the provision and the values and use of ESS (Nemec and Raudsepp-Hearne 2012; De Souza and Verburg 2010).

There has been research on mapping and modelling ecosystem services, but adequate data and models are often not available (Nemec and Raudsepp-Hearne 2012; Chen et al. 2009). Primary data, in spite of its importance is, in most of cases, resource intensive to obtain, difficult to gather across large areas over long periods of time, and sometimes expensive (Pettorelli et al. 2014; Chen et al. 2009). Therefore, secondary data which consists of spatial units, like watersheds and land cover classes, are often used as proxies for evaluating ESS (Eigenbrod et al. 2010). According to Eigenbrod et al. (2010), maps based on proxy data are useful for broad scale patterns in ESS, but are of limited help for the identification of areas where there are provision of multiple ESS. Nevertheless, it has been demonstrated that the complementary use of remote sensing and ecosystem modelling in studies of ESS is quite useful, for example in cases of terrestrial carbon cycling (Turner et al. 2004). Furthermore, remote sensing contributed to the indicator framework (Decision VIII715) for the Convention on Biological Diversity (CBD) (Strand et al. 2007) and was employed in several studies for assessing biodiversity (Maxted 2012; Nagendra and Rocchini 2008; Salem 2003; Nagendra 2001); biodiversity data (Flemons et al. 2007) and loss of agro-biodiversity (Garcia-Yi 2014).

4.1. Scaling from Pixel to Regional Level

Characterization of ecosystems requires data which covers large spatial areas and which, in most of the cases, are not available or are difficult to obtain with field based techniques. Remote sensing offers a good option for gathering this data. In addition, for studies spanning different spatial scales remotely sensed data can be combined with field collected data. Such data may include information on land cover, vegetation cover, habitat, forest structure, and forest function among others (Wulder et al. 2004).

Developments in remote sensing technology have resulted in new capabilities for data capturing and processing. It is therefore possible to produce and analyze images at very high spatial resolution. (Cohen and Goward 2004; Wulder et al. 2004). For research on ecosystem services, the resolution of data used to map ESS relies on the service of interest. ESS with site-specific processes, such as pollination, demand higher resolution data. Generic services, such as carbon sequestration, may be adequately dealt with using data of coarser resolution (Nemec and Raudsepp-Hearne 2012).

A wide range of remote sensing scale datasets is available, which can be employed according to the resolution requirement of a specific environmental service. For example, IKONOS imagery works at high resolution level, whereas MODIS has a low spatial resolution. Mallinis, Pleniou, and Koutsias (2009) employed various image analysis techniques, including IKONOS and MODIS, for assessing and mapping burned areas at local, regional and global scale. Martinuzzi et al. (2008) employed Landsat for mapping tropical dry forest habitats. Gómez et al. (2011) used QuickBird for studying forest structures in Spanish Central Range.

4.1.1. Very High Spatial Resolution

Over recent years, several fine spatial resolution systems became operative. These systems allow the characterization of ecosystems over a range of scales. In general, very high spatial resolution refers to resolutions of less than 5m (Maini and Agrawal 2014).

Very high spatial resolution imagery can help assess the accuracy of remote sensing data from moderate or coarse spatial resolution (Upreti et al. 2015). For instance, Boyle et al. (2014) assessed the accuracy of Landsat based large scale data of Interior Atlantic Forest in Paraguay mapping against pattern detectable with very high resolution IKONOS images. Very high resolution data was also employed in the assessment of biodiversity in forests (Getzin et al. 2012); mapping and monitoring riparian forest patterns (Johansen et al. 2007); monitoring structural diversity in a savannah system (Levick and Rogers 2008); and assessing, monitoring and conserving biodiversity in India (Singh et al. 2010).

Nagendra and Rocchini (2008) mentioned that although very high spatial resolution satellite imagery is a helpful data resource, it is, at the same time, an underutilized powerful tool for tropical research on biodiversity. This can perhaps be partially explained by the high cost of high spatial resolution imagery, with a price of approximately US$ 3,000 – 5,000 for 10 km^2 (Boyle et al. 2014; Wang et al. 2010). Prices, however, have a tendency to decrease with the emergence of more sensors and greater competition in the future (Wang et al. 2010).

For the time being, the two most widely used providers of very high spatial resolution data are the *IKONOS* and *QuickBird systems*, which are described in the following.

a. **IKONOS** is commercial satellite high resolution imagery. Its resolution is at 1m panchromatic (PAN) and 4 meter multispectral (MS). Among its principal

advantages are its good location knowledge in near real time and offline (Kramer 2002). Applications of IKONOS include urban and rural mapping of natural resources, natural disasters, agriculture and forestry analysis, and mining among others. In the case of biodiversity, IKONOS imagery can be used for the quantification and evaluation of the spatial structure of critical habitats and how it affects endemic species, thus providing baseline information for the monitoring and management of biodiversity (Wang et al. 2010).

b. *QuickBird* is a system with multispectral imagery at resolutions of 2.4 - 2.8m and panchromatic imagery 0.6-0.8 m. QuickBird allows for the direct identification of certain species and assemblages of species (Upreti et al. 2015). Neukermans et al. (2008) employed QuickBird satellite image for automated mangrove stand recognition. The Nature Conservancy used QuickBird data for a global assessment of biological diversity and conservation (Writer 2004).

4.1.2. High Spatial Resolution

High spatial resolutions range from 5m - 30m obtained with panchromatic or multi-spectral sensors or analogue camera systems (Maini and Agrawal 2014). An important provider of data of high spatial resolutions is the Indian Remote Sensing Satellite (IRS). Satellites of the IRS programme have a temporal resolution of 24 days and its images are suited for advanced applications in vegetable dynamic, crop production estimations and for supporting disaster administration and natural resources inventories (Indian Space Research Organisation 2015; Upreti et al. 2015). Chettri et al. (2013) employed high spatial resolution IRS and medium spatial resolution images for describing spatial and temporal land use and land cover change from the period from 1976 to 2010 in the Koshi Tappu Reserve in Nepal.

4.1.3. Medium Spatial Resolution

Medium spatial resolutions range from 30 - 250m and are obtained by multi-spectral sensors (Maini and Agrawal 2014). Data sets of medium spatial resolution have a low cost per unit area. Images are used for the global observation of land surfaces. An important provider of remote sensing data of medium spatial resolution is the LANDSAT satellite system. LANDSAT is an important element of NASA's Earth Observing System, providing multi-spectral imagery at a horizontal resolution of 28.5 - 90m. Launched in 1972, the LANDSAT satellite series constitutes one of the longest continuous records in Earth observation. Uses of LANDSAT include the mapping of landcover change (forest change in tropical and temperate regions, urbanization, etc), monitoring of agricultural productivity and mapping crop types in agricultural regions, monitoring of wetland health, mapping geologic resources, targeting of habitats for vector-borne disease eradication, forest classification, mapping of bird habitats, or estimating above ground biomass in forest

plantation (Cohen and Goward 2004); (LANDSAT 2015). As related to biodiversity, the effects on land- use change on biodiversity and ESS in tropical montane cloud forests of Mexico have been assessed relying on LANDSAT data (Martínez et al. 2009), and crop pollination by native bee communities in California has been studied (Kremen et al. 2004).

4.1.4. Low Spatial Resolution

Low spatial resolution refers to resolutions of several hundred meters. Images are taken by several multi-spectral sensors like GEOS, Meteosat, NOAA, Vegetation and Modis.

A lower resolution frequently corresponds to a higher repetition rate, meaning that within a short interval the satellite investigates the same area, which implies a higher temporal resolution. Low spatial resolution data have a very low cost per unit area and are very suitable for environmental and agricultural applications (Upreti et al. 2015).

MODIS (Moderate Resolution Imaging Spectroradiometer) is an instrument launched into the Earth's orbit by NASA in two satellites, Terra and Aqua. The instruments capture data in 36 spectral bands and varying spatial resolutions (2 bands at 250m, 5 bands at 500m and 29 bands in 1 km). Together, the instruments image the entire Earth every one to two days. MODIS is also employed for developing Earth system models for predicting global change in order to assist policy makers in environmental decisions (NASA 2015a). MODIS was employed in several studies; to map burned areas at regional level (Boschetti et al. 2015); to map land cover in Greater Yellowstone Ecosystem, USA and the Pará State, Brazil to focus on biodiversity (Wessels et al. 2004); to calibrate Landsat data for exhaustive high spatial resolution cover and clearing in the Congo River Basin (Hansen et al. 2008).

4.1.5 Pansharpening Image

Pansharpening image is a technique of merging high-resolution panchromatic imagery with lower resolution multispectral imagery with the aim to create a single high resolution color image. This technique contributes to increasing image quality. Lin et al. (2015) found that pansharpening image played an important role on the classification accuracy on Changes of Land Use and Land Cover (LULC). The classification accuracy increased by 12% on average compared to the ones without pansharpening.

4.2 Open Access Datasets

There is no single approach for estimating or mapping ESS, as they are more or less related to a particular ecosystem, but improvements in remote sensing may also provide better data on the distribution of ecosystem and ESS (Ayanu et al. 2012). Freely available satellite images and associated databases permit for remote sensing analysis of ESS in regions where few data are available. In the next paragraphs, several open access remote sensing datasets, using spatially explicitly approach and GIS datasets, are described.

4.2.1 HarvestChoice

HarvestChoice is an initiative with the objective of contributing to increasing productivity and profitability of farming in Sub-Saharan Africa. In order to accomplish this goal, HarvestChoice has produced a wide range of knowledge products which comprise maps, datasets, publications, tools and spatial and economic models. Moreover, HarvestChoice is working in cooperation with other institutions to develop more tools, e.g. a collaboration with IIASA for the Spatial Production Allocation Model (SPAM) project (see section 4.2.2.). This initiative is coordinated by the International Food Policy Research Institute (IFPRI), the University of Minnesota and is supported by the Bill and Melinda Gates Foundation (Harvest Choice 2015; Bacou 2013).

HarvestChoice data is organized into a matrix of 10km x 10km grid cells in Sub-Saharan Africa. The platform provides information on mix of farming, and cultural and socio-economic conditions. In addition to the datasets, HarvestChoice offers interactive tools, such as Mappr and Tablr, for creating own scenarios through the manipulation and overlapping of layers of more than 700 agricultural indicators. Some examples of spatially explicit data sets accessible in HarvestChoice are; the spatial distribution and performance of agricultural production systems; the spatial distribution and severity of production constraints (e.g. pests and diseases, drought, low soil fertility); spatial variation in national and local policies and regulations (e.g. adoption of a new technology) (Harvest Choice 2015).

4.2.2 SPAM (IFPRI/IIASA)

The Spatial Production Allocation Model (SPAM) provides spatially disaggregated crop production for 42 crops. A new interactive website was developed by IFPRI and the International Institute for Applied Systems Analysis (IIASA) at www.mapspam.info. The website includes maps that were produced using satellite images and fine-tuned by a global crop mapping community in cooperation with other CGIAR centres and local collaborators. The maps can be overlaid with other geospatial datasets to assist with aspects of food security, such as crop productivity, ecosystems services, climate change and social welfare (MapSPAM 2015; HarvestChoice 2015).

4.2.3 Natural Earth

Natural Earth is a public domain map dataset. It contains cultural, physical and raster (basemap) data. GIS datasets are at a global scale. Natural Earth is supported by the North American Cartographic Information Society (NACIS) (Natural Earth 2015).

4.2.4 USGS Earth Explorer

The U.S. Geological Survey through its Earth Explorer provides one of the largest open access databases of satellite and aerial imagery. It has a user friendly interface and provides remote sensing data (Landsat, global land cover, among others) (USGS 2015).

4.2.5 NASA's Socioeconomic Data and Applications Center (SEDAC)

This website provides geographic information about human interactions with the environment. SEDAC has a wide variety of free global GIS data of coarse resolution. Global socio-economic data such as population, poverty, governance, health or infrastructure are associated with data on agriculture, climate, conservation, land use, sustainability, hazards, marine and coastal, urban and water (NASA 2015b).

4.2.6 Open Topography

The Open Topography website provides a portal to high spatial resolution topographic data and tools and makes LiDAR (Ligth Detection and Ranging) data freely available. This data is used to make high resolution maps, with a applications in forestry, remote sensing, and geomatics among others (Open Topography 2015).

4.2.7 DIVA-GIS

DIVA-GIS offers free GIS datasets for any country in the world. This dataset is very helpful for mapping and analyzing biodiversity data (e.g. distribution of species) (DIVA-GIS 2015).

4.2.8 UNEP Environmental Data Explorer

The UNEP Environmental Data Explorer is an online database that holds more than 500 variables, such as national, regional and global statistics, as well as geospatial data sets (maps). This is the data used by UNEP and its partners in the Global Environmental Outlook (GEO) report and other integrated environment assessments. Data covers forest, climate, freshwater, emissions, population, disasters, health and GDP (UNEP 2015).

4.2.9 FAO GeoNetwork

FAO GeoNetwork is a global open source GIS dataset. It provides satellite imagery and spatial data to support sustainable development in agriculture, food security and fisheries (GeoNetwork 2007).

4.2.10 NASA Earth Observations (NEO)

NEO provides global satellite imagery data. Over 50 global datasets are represented with NASA´s Earth observations. Data is constantly updated and it is accessible in different formats including JPEG, PNG, Google Earth and GeoTIFF (NASA 2015c).

4.2.11 ISCGM Global Map

ISCGM Global Map offers free GIS data. Two important datasets are the global land cover, and land use and vegetation. Global Map also has data on boundaries, drainage, transportation, population centers and elevation. This dataset has been developed under the cooperation of National Geospatial Information Authorities (NGIAs) of respective countries and regions. The data is updated every five years and the digital geospatial information has eight layers developed with consistent specifications (ISCGM Global Map 2015).

5 Summary and Outlook

This literature review on "Integration of Ecosystem Services in Agricultural Economic Models" has reviewed available data, some biophysical process models and different agricultural economic modelling approaches. For the assessment of ESS and biodiversity, every approach has its own strengths and weaknesses. At lower scales of aggregation, such as the household and farm levels, ESS and biodiversity can be better integrated but results may not be generalized and extrapolated to larger spatial scales. The strength of landscape models lies in their capability to provide information on the provision and value of multiple services in space and time. Economic aspects, however, are often ignored in these models. Partial equilibrium (PE) models have a big potential for the analysis of ESS and biodiversity in a comprehensive manner, but these models operate at a relatively higher level of spatial resolution and are limited to the agricultural sector. General equilibrium models allow cross-sectoral linkages but may not capture much detail of households, farms or biodiversity and ESS. Given these strengths and weakness of models at various scales, to fully analyze the impact of biodiversity and ESS in the agricultural systems contexts, it is preferable to link analyses across models at different scales. A summary of the different models reviewed is presented in Tables 1-4.

There is no single model for estimating or mapping ESS and biodiversity and their trade-offs in different agricultural systems. Future collaborative work between different economic modelling approaches may be carried out. Outputs of household/farm level models could be employed in partial equilibrium and general equilibrium models. Spatial data can be very useful for scaling models.

Based on the literature review and the discussions on the workshop, major areas where future work should focus on, include:

- Develop a common language among the researchers where environmental services (ESS) have been clearly identified and the definition of key concepts of biodiversity and related variables have been defined.

- Develop a methodology to identify appropriate spatial and temporal scales of provision of ESS. For this issue, it was suggested to develop a typology of questions related to biodiversity and socio-economic impacts, which may help to find the most suitable models to use.
- Develop a meta database of available data in a format that could be useful for the different types of models.
- Explore how the linkages between ESS and biodiversity differ by ecosystems and different agricultural management in order to understand the provision of ESS.
- Link model outputs from different scales, impacts on ESS/biodiversity and data across scales.

This review focused on quantitative models, but qualitative analysis and studies using descriptive statistics are complementary to the quantitative models. Qualitative studies may contribute with relevant insights that are difficult to capture in quantitative models. This information could be used by modellers to include new variables, as well as establish causal relationships in their models and determine the different scenarios for model simulation.

Table 1. Household / Farm Models

	FSSIM	MPMAS	ARIES
Institution	European Commission	University of Hohenheim	ARIES Consortium
Model Framework	Model works from greater disaggregated data upward starting with household and biophysical data	Model works from greater disaggregated data upward starting with household and biophysical data.	Model works from greater disaggregated data upward starting with household, biophysical data and local GIS data.
Temporal Dynamics	Static	Dynamic	Dynamic
Land Use Representation	Agricultural land	Agricultural land (livestock), forest	Agricultural land, forest
Database	SEAMLESS database	Own database, FAOSTAT, EUROSTAT, National	ARIES Geoserver
Externalities/ESS	Applications have covered soil erosion; N leaching; water drainage; soil fertility, organic matter; pesticide volatilization, runoff and leaching; erosion peak, runoff peak, average farm N surplus, farm gate N efficiency	Applications have covered soil erosion, soil fertility, pesticide runoff, carbon storage, crop diversity	Applications have covered water quality, soil erosion, carbon storage, and aesthetic value of landscapes
Strengths	Covers many externalities Very detailed representation of agricultural activities	Good representation of land activities and externalities Assesses agents and environment over time	Uses relatively limited amount of data (public domain)
Limitations	Perfect market assumption (labour, land and capital) Inflexible demand system (linear expenditure system)	The mixed integer programming (MILP) approach of modelling farm decision making demands parameterization of all possible decision alternatives	No perennial crops and livestock modules
Options for Improvement	Can incorporate inter-temporal dynamics Can include other ESS	Can include other ESS Can incorporate decision-making under uncertainty Collective action (relevant for community projects) can be considered	Can incorporate inter-temporal dynamics Can include other ESS

Source: Author summary of literature

Table 2. Landscape Tools/Framework

	InVEST	IMAGES
Institution	Natural Capital Project	University of Wageningen
Model Framework	Model works up from greater disaggregated biophysical data on land cover, marine habitats, and ocean uses	Model works up from greater disaggregated stakeholders input and landscape data
Temporal Dynamics	Static	Static
Resolution	Spatial units of any resolution	Few square km
Database	Own database	
Externalities/ESS	Biodiversity, water quality, soil conservation, carbon sequestration, pollination, managed forestry and non-timber forest product production, agricultural production, housing (property) values, cultural and tourism	Applications have included soil fertility, loss of nutrients, biodiversity
Strengths	Consistent and flexible toolbox for ecosystem service assessment Models can be run stand alone or combined to assess trade-offs Generates site-specific scenarios Stakeholder consultation in planning process and alternative scenario development	Supports discussions and inform decision making by stakeholders
Limitations	Quality of output is dependent on the suitability of the input used to address the study area specific processes and fit the available data It currently lacks an agricultural component and its coverage of socio-economic sectors are very limited	Not validated at the level of the whole landscape system Static approach
Options for Improvement	Better linkages to socio-economic and agricultural models are needed	Validation based on quantitative and empirical data Inclusion of dynamics

Source: Author summary of literature

Table 3. Partial Equilibrium (PE) Models

	IMPACT	GLOBIOM	CAPRI	MAgPIE
Institution	IFPRI	IIASA	University of Bonn	PIK
Model Framework	Model starts working down from highly aggregated biophysical and macroeconomic data	Model mostly starts working from highly disaggregated biophysical and macroeconomic data but the algorithm operates at an aggregated level	Model can work up from disaggregated data or down from aggregated data	Model starts working down from highly aggregated biophysical and macroeconomic data
Regional Coverage	Global, 159 political regions	Global, 30 regions	EU	Global, 10 regions
Resolution (production side)	320 spatial units	Detailed grid cells (>200,000)	280 regions, around 2000 farm types	Detailed grid cells (aprox. 60,000)
Land Use Representation	Crop land, pasture, forest, other uses	All land uses in dynamic framework	Crop land, pasture	Crop land use in dynamic framework, other lands static
Database	FAOSTAT	FAOSTAT, SPAM	EUROSTAT, FAOSTAT, OECD, FADN	GTAP, FAOSTAT
ESS	Water, N leaching	Water, biodiversity, carbon sequestration	Carbon sequestration, biodiversity	Water, soil nutrition
Strengths	Good commodity coverage (> 50)	Includes agriculture, forestry and bioenergy sectors	Detailed information of agricultural sector	Detailed information of agricultural sector
	Relatively high disaggregation on demand side (>150 regions)	Great detail at grid cell level with spatially explicit representation of agricultural technology	Allows incorporating feedbacks of changes in biodiversity and ESS on yields	
		Dynamic land use change		
Limitations	Coarse spatial resolution	Limited biodiversity coverage	Spatial coverage limited to EU	Does not contain prices, only costs
	Forest sector lacking			
	Limited ESS coverage			
Options for Improvement	Increase spatial resolution Improve representation of land use change Incorporate externalities to assess biodiversity and ESS	Can include other ESS	Include other regions Incorporate externalities to assess biodiversity and ESS	Incorporate externalities to assess biodiversity and ESS
		Incorporate decisions under uncertainty		
		Incorporate collective action as relevant for community projects		

Source: Author summary of literature

Table 4. General Equilibrium (CGE) Models / Integrated Assessment Model (IAM)

	GTAP	MIRAGE	IMAGE
Institution	GTAP Consortium	IFPRI, CEPII	PBL, Netherlands Environmental Assessment Agency
Model Framework	Model starts working down from highly aggregated biophysical and macroeconomic data	Model starts working down from highly aggregated biophysical and macroeconomic data	Model starts working down from aggregated biophysical and macroeconomic data
Regional Coverage	Global, 129 regions	Global (1 EU region + 10 world regions)	Global, 26 regions
Resolution (production side)	129 regions	Regional level, with land split into up to 18 agro-ecological zones	Grid cells (5 x 5 degrees)
Temporal Dynamics	Static	Recursive dynamic	Recursive dynamic
Land Use Representation	Crop land, pasture, forest, other uses	Crop land, pasture, forest, other uses	Crop land, pasture, forest, other uses
Database	GTAP database	GTAP database, MAcMAp-HS6 database and others	FAOSTAT and other data
Externalities/ESS	Biodiversity applications have been conducted	Carbon emission implications of policies have been examined	Biodiversity, water/air pollution, CO_2 and non-CO_2 emissions, carbon/ nitrogen cycle, water stress, land degradation and other ESS are possible
Strengths	Analysis of economy wide effects	Analysis of economy-wide effects	Integrated assessment
	Analysis of specific policies, including environmental policies	Analysis of specific policies including environmental policies	Many feedbacks incorporated
			Cover a wide range of externalities and ESS
Limitations	Provides analysis at aggregate level	Provides analysis at aggregate level	Being a collection of many different sub-models it may be challenging to navigate and use
Options for Improvement	Improve linkages to incorporate externalities to assess biodiversity and ESS	Improve linkages to incorporate externalities to assess biodiversity and ESS	More user friendly documentation and improved ease of model access will help

Source: Author summary of literature

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