Deliverable 3.1

Operational relationship between analytical tools available in the framework

This document is part of WP 3 'Systems analysis protocols'
of the EU FP 7 SAT-BBE project:
Systems Analysis Tools Framework for the EU Bio-Based Economy Strategy

30 November 2014

Project consortium and contribution

	Short name	Full name	Member State	Contributed to this document
1	IFPRI	International Food Policy Research Institute	USA	X
2	LEI-WUR	Agricultural Economics Research Institute	Netherlands	X
3	UU	Utrecht University	Netherlands	X
4	EFI	European Forest Institute	Finland	X
5	WI	Wuppertal Institute	Germany	X
6	IIASA	International Institute for Applied Systems Analysis	Austria	X
7	VUA	Vrije Universiteit Amsterdam	Netherlands	X
8	TI	Johann Heinrich von Thünen Institut	Germany	X

Lead authors:

IFPRI:	Siwa Msangi, David Laborde
VUA:	Peter Verburg, Sarah Wolff, Willem Verhagen, Reinhard Prestele
LEI-WUR:	Myrna van Leeuwen, Edward Smeets, Hans van Meijl
WI:	Stefan Bringezu, Meghan O' Brien
IIASA:	Hugo Valin
UU:	Yannis Tsiropoulos
EFI:	Lauri Hetemäki, Marcus Lindner, Alexander Moiseyev
TI:	Franziska Junker, Ralf Döring

Table of Contents

1 Introduction

The objective of the SAT-BBE project is to design systems analysis tools framework for monitoring the evolution and impacts of the bioeconomy. The development of this framework is structured in three Work Packages (WPs): 1). Scoping and definition of the systems analysis framework (WP 1), 2). Tools for evaluating and monitoring (WP 2) and 3). Systems analysis protocols (WP 3). WP 1 and WP 2 have been finalised and the results are used as basis for the final integrated systems analysis tools framework that will be delivered in WP 3. More specifically, the objectives of WP 3 are:

1) To identify appropriate analytical tools (in terms of operational effectiveness and efficiency) to be used for a systems analysis of the bio-based economy within the EU.
2) To conceptually specify and develop the possibilities for linking tools through software development.
3) To elaborate the interfaces with the analytical tools for non-specialists, as is deemed practical.
4) To communicate the solution found for the design of the systems analysis tools framework.

The first two aspects are discussed in Deliverable 3.1 '*Working paper on the operational relationship between analytical tools available in the framework'*. The outcome of Deliverable 3.1 is a detailed examination of possible operational relationships between the analytical tools identified in WP 2, taking into consideration their current (in)compatibilities in the use of output for an integrated analysis of the state and trajectory of evolution and impacts of the EU bioeconomy. The objective of Deliverable 3.2, which is titled '*Software routines to interact with the quantitative tools used within the framework*', is to conceptually develop user-friendly software routines prepared for providing non-specialists with the means to interact with the quantitative tools used within the framework (user interfaces for specific applications or enquires). Not all tools and models generate output that is easily 'readable' (intelligible) with regard to specific issues and interpretation of model output is a matter of specialised training. The use of complex models and tools is not necessarily practical for policy makers and other non-specialists and therefore it is essential to make these models and tools, or the results of these models and tools, accessible and useable to them. Creating a user-friendly interface can be a useful first step towards overcoming some of the barrier they may face in accessing these tools, but other steps are needed as well. Deliverable 3.1 and 3.2 are combined in Deliverable 3.3 in which the final framework for systems analysis tools for monitoring the evolution and impacts of the bioeconomy is presented.

The approach used in this deliverable is explained in Section 2. In Section 3 a conceptual design for a user interface of the SAT-BBE systems analysis tools framework is developed. In Section 4 relevant examples of user friendly interfaces are presented and discussed. The results of Section 2, 3 and 4 are summarized in Section 5.

2 Approach

The objective of this deliverable, as formulated in the description of work (DOW) is to lay out the operational relationship between the various modelling tools that will support the analysis of the knowledge-based bioeconomy. The essential elements that are needed to describe the evolution of the bioeconomy have already been laid out in the previous deliverables of the project – but this work package component will make the possible nature of the linkages between them more concrete and specific to the various modelling tools that are used within the research consortium. By describing the operational relationships between the analytical components, the possible methods for linkage, and the challenges that are faced in carrying this out – we will lay the groundwork for the actual design and implementation of a workable set of protocols. This exercise will also serve to highlight the many complex interactions that are considered in the systems analysis tools framework developed in this project.

It should be noted here that the actual implementation of modelling linkages, through workable software routines and protocols goes beyond the objective, scope and resources available in the SAT-BBE project. But we will proceed with a conceptual design of the linkages and interfaces that will allow the various models to make the best use of the information that each of them provides, so that a blueprint for later implementation can be provided.

In this deliverable we will, first, motivate the reasons for linking the analytical tools that are described within the research consortium, to address the research questions posed in this study. We will then discuss the broad classification of analytical tools that are used (Section 3.1), before giving a description of the key models that are being considered (Section 3.2). In Section 3.3 we describe the key 'entry points' that will be useful for creating operational linkages between the tools. Following this, we will talk in more detail about the operational linkages themselves (Section 4), before drawing conclusions in Section 5.

This deliverable is compiled by IFPRI, with primary assistance from LEI and VUA, and key inputs from TI, EFI and WI.

2.1 Key motivation for modelling collaboration

The research consortium that has been assembled to study the key characteristics of an evolving, knowledge-based bio-based economy possesses a unique set of tools that can capture the key elements of the bioeconomy and its evolution under alternative trajectories of technological change, socio-economic evolution and environmental conditions. Each member of the research consortium possesses a set of analytical tools that are suitable for examining a particular aspect of the bioeconomy – although no one consortium member possesses an all-encompassing framework that can address the character and evolution of the bio-economy in its entirety. It is for this reason that a constructive collaboration between models must be designed to take the best advantage of the available analytical tools that are available.

There are various levels of model collaboration that are possible within the research consortium – each of them representing a differing level of complexity, consistency and computational difficulty. In their analysis of biomass supply and demand, Wicke et al (2014) describe the different kinds of modelling collaboration that are possible between economic and biophysical models. Drawing from their characterization, we can make a distinction between (1) the mere alignment and harmonization of models through their drivers of change and underlying assumption; (2) a close comparison of models in order to make systematic studies of methods, sensitivities, assumptions and results; and (3) a close integration of models, where models are either loosely or tightly-coupled together. These types of modelling collaboration and coordination represent a successively increasing levels of computational intensity and research design complexity – with the coupling approach being the most challenging and time-consuming. Despite the challenges of the coupling approach, we see it as among the best ways of illustrating the critical feedbacks and interactions between the various parts of the socio-economic and biophysical elements that characterize the wider bioeconomy and its evolution from having a fairly heavy dependence on fossil-based sources of energy and materials.

The operational relationships that we wish to draw attention to in this study, are those which afford a straightforward linkage between the critical socio-economic drivers of change (population- and price-driven consumption and supply dynamics) and the biophysical realities imposed by the availability of key natural resources such as water, land, fossil-based energy resources and other minerals. This will require there to be interaction between models that capture both economic and biophysical processes, in order for these linkages to be understood and captured within our analytical framework. The characteristics of the bioeconomy that are of key importance within this framework are the opportunities for making better use of bio-based co-products that come from manufacturing processes (perhaps as inputs into other production activities) – as well as recovering waste products from higher in the value chain (even at household level) that contain useful bio-based materials. This requires an explicit representation of processes and conversion efficiencies at the sector-level, that must be taken into account by the available modelling tools.

In the next sub-section, we go into more detail about how the important components of the bio-economy could be captured within our analytical framework.

2.2 Conceptual underpinnings of the analytical framework

In order to have a better understanding of how the key analytical tools should fit together to capture the key features of the bio-based economy and its steady evolution over time, we point the attention of the reader to the schematic shown below.

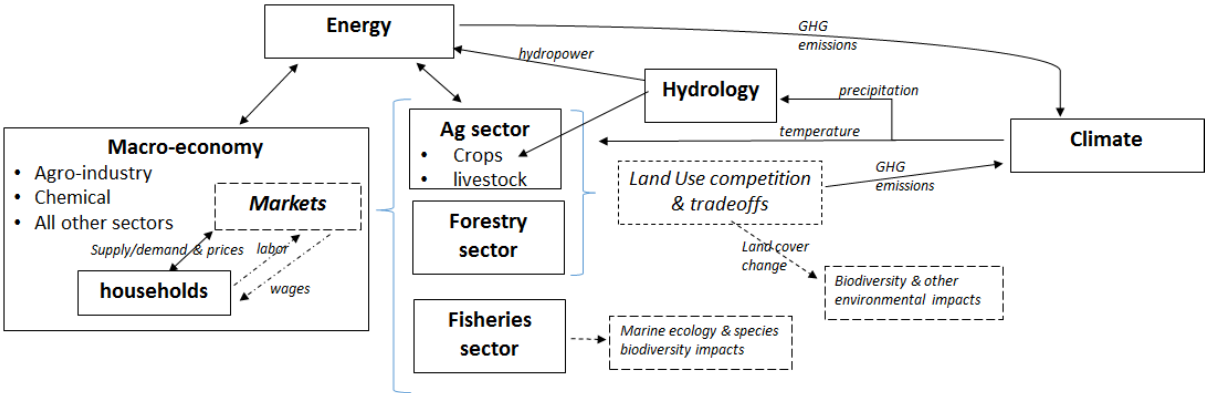


Figure 1: Key components needed for monitoring the bio-economy

In this schematic, we see important interactions between the natural resource base (land & water) and the sector-specific processes that rely upon them (agriculture, forestry) – and how they interact with the rest of the macro-economy. The energy sector supplies needed inputs for manufacturing and household consumption, while also obtaining bio-based products that can come from the agriculture and forestry sectors (in the form of bioenergy feedstocks). The climatic system that determines patterns of precipitation and temperature that are critical for agriculture and the surface water hydrology that affects the rest of the economy is also influenced by the levels of greenhouse gas (GHG) emissions coming from various sectors and human-driven activities (such as land-clearing). This is a complex process that is difficult to model explicitly, but must be taken into account within the overall framework.

In the conceptual outline shown in Figure 1, we see that there are some important aspects of environmental quality that are associated with changes in how land-based and marine-based resources are used. The conversion of land cover from natural vegetation and forestry to managed pasture for livestock or cropland for agricultural production might entail loss of natural habitat and negative impacts on species biodiversity in the landscape. Within a marine environment, the continued pressure of fishing could also change the underlying ecological dynamics of fish species and cause changes in species biodiversity in oceans. These are complex processes to model, given the wide range of land- and marine-based species that are present in any given geographical area, and relatively few modelling attempts have been able to capture this well.

Since we do not explicitly model all the aspects of this conceptual framework within our research consortium, we will describe the tools we do have, in the next section. This will allow the reader to better understand the particular aspects of the bioeconomy that we can address in a straightforward way, with the available tools – and those aspects that would require further efforts to address in future research.

3 Description of various tools and models within the systems analysis framework

3.1 Broad classification of models used

Since we will be describing the possible operational relationships across a variety of models – it is best to start off with a clear description of model types, so that the reader can get a better sense of how they differ and what the points of linkage are. The challenge of dealing with a broad variety of models is greatly helped by understanding the differences (and similarities) between them.

Listed below are some important classifications that we will apply across the analytical tools that we will be describing

1) **Global**: A number of the models we will describe will have global coverage of all regions of the world (even if not all sectors). Such models have to account for how things “add-up” across the world, whereas sub-global models can ignore things outside of their region of interest. The level of detail in which the different global sub-regions are defined will vary – with some treating the EU (or other regions) in finer “resolution” compared to other models.

These differences are often dictated by research interest, as well as computational tractability.

2) **Regional**: A number of the models focus on key regions of the world – such as the EU. By having a narrower geographical focus, more detail can be brought to how particular sectors are treated. There is often sub-regional disaggregation of such models, to allow for more granular analysis – up to the limit that available data will allow.
3) **Partial-equilibrium:** Among the economic models discussed, a number will focus on particular sectors of interest (such as agriculture) and model how those markets reach equilibrium, while ignoring how certain factor markets or other sectors in the region or globe interact with them. Partial-equilibrium (PE) models fall into this category. Often this is done for reasons of research interest, data availability and/or computational ease. By focusing on particular sectors, certain details of production or resource usage (for example) can be elaborated upon – even with explicit bio-physical representations or through the representation of complex underlying processes. Not all factors of production may be priced, however, which assumes (implicitly) that they are unlimited in availability.
4) **General-equilibrium**: In contrast to partial-equilibrium (PE) models, applied (or computable) general-equilibrium (GE) models account for economy-wide interactions that are of relevance to how production and consumption activities affect each other, and enforce key macro-economic balances that ensure that all productive factors are priced and that all resources are 'paid for'. The circular linkage that describes how payments for factors are distributed among various agents (especially households) and affect the final demand for the products themselves, is a key feature of GE models and allows for feedback effects that PE models cannot capture. Due to the additional comprehensive treatment of the larger macro-economy, GE models tend to be less detailed on the production side, and typically do not go into the level of detail that PE models can afford to – due to computational constraints. Given the emphasis on 'payments' and monetary flows within the economy, GE models are often less amenable to linking directly with bio-physical process models that focus on supply-side details.

With these classifications in mind, we show a rough schematic below (Figure 2) of how various tools used within the systems analysis of the knowledge-based bioeconomy fall into various categories or typologies.

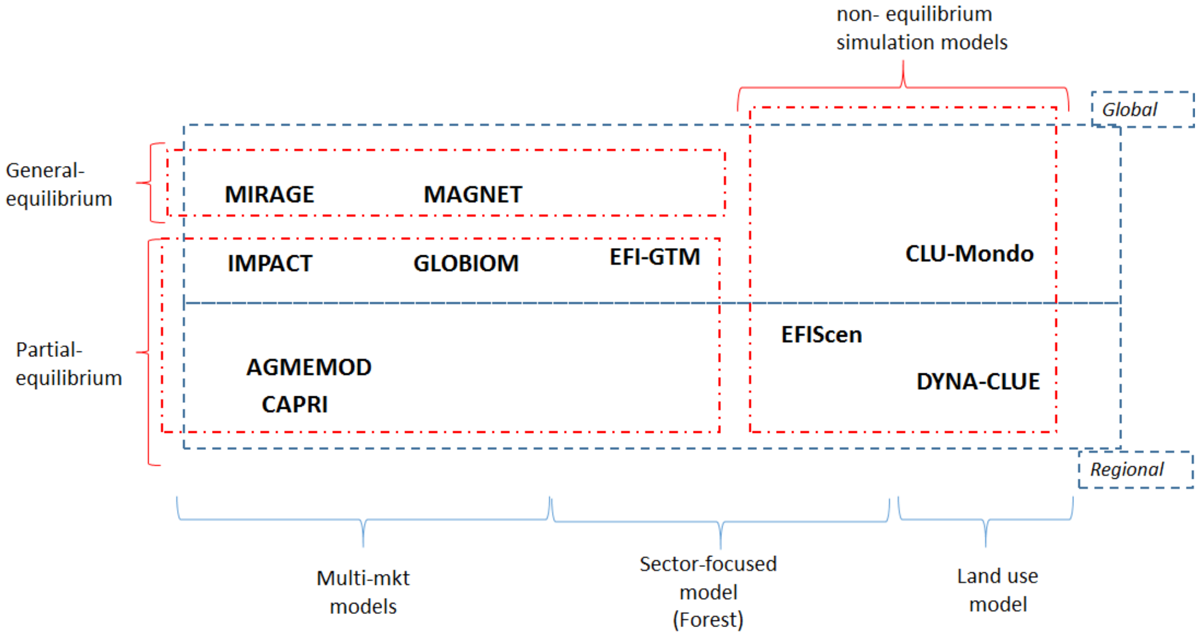


Figure 2: Classification of various models within the research consortium

Across the broad classes of global/regional or general- and partial-equilibrium models – we also see that some models cover a number of markets, whereas others focus on a specific sector. These differences will dictate the degree of linkage that these models might have with each other, and which might better capture certain detailed aspects of the bioeconomy.

In the following sub-section, we describe the essential features of these models, so that the reader can begin to appreciate the similarities and differences between them – and possible entry points for linkage.

3.2 Brief description of various models

Following here, we describe the various modelling tools that are being considered within the analytical framework for monitoring the evolution of the bioeconomy. We include the description of both partial- and general-equilibrium models, as well as those which are global or regional in nature – as was described in Figure 1. Due to space constraints, we are not able to go into great detail on any of the models, but provide a number of useful references that will provide extra guidance to the interested reader.

3.2.1 MIRAGE

The MIRAGE model is a global CGE model that has been developed over time by researchers in CEPII and IFPRI, and shares the canonical structure for a global CGE model that is found in models such as the ENVISAGE model (used at the World Bank, OECD and FAO) as well as the global CGEs within the GTAP family of models. MIRAGE has been used widely for a number of analyses on trade liberalization (Bouet and Laborde 2010, 2012), biofuels policy (Laborde 2011, Laborde and Valin 2012) and environmental impacts, using variants to its structure, such as the MIRAGE-BioF and

MIRAGE-HH versions. The country coverage in MIRAGE can be extended up to 129 GTAP-defined regions, although it is typically used for 30-40 aggregate regions at a time, and is frequently run over an outlook period that extends up to the year 2050.

3.2.2 MAGNET

The MAGNET model (previously known as 'LEITAP') is a global CGE model developed at LEI, and which has a flexible, modular structure that enables its adaptation to a number of research applications (Woltjer et al 2011). Sharing the same canonical structure of MIRAGE and other comparable global CGE models, it has been applied to the study of biofuels and land use change with the additions of appropriate modules., as well as to the impact of European Common Agricultural Policy (CAP) shocks, and other policy regimes. The MAGNET model can be extended up to 134 GTAP-defined regions, and has been used for outlook projections to the year 2100.

3.2.3 IMPACT

The IMPACT model is a global, partial-equilibrium, multi-market model that focuses on agricultural commodities, and which has been used, primarily, for medium- to long-term projections (Rosegrant, 2012). IMPACT models the interactions between water availability and food production by making the crop yields within the economic multi-market model respond to allocations of surface water (or rainfall, in the case of non-irrigated crops) that come from an optimization-based, inter-sectoral water allocation model. The IMPACT model has been applied to the study of agricultural supply and demand trends, and how they are affected by new product streams such as biofuels (Tokgoz et al 2012) and fisheries products (Msangi et al. 2013).

3.2.4 GLOBIOM

The GLOBIOM model is a global partial-equilibrium model, that integrates the agricultural, bioenergy and forestry sectors into one framework (Schneider et al 2011). The model covers 28 global regions in demand and trade, but models production at the grid level. Particular detail is put on the mechanism of land allocations to crops, forest, grazing lands and the underlying tradeoffs and resource completion. The model uses biophysical models to define crop and animal productivity potential for the agricultural sector, under given climatic conditions and management regimes. Some key applications of GLOBIOM have been to the study of environmental impacts coming from biofuels production (Havlik et al 2011) and livestock production (Havlik et al 2013).

3.2.5 AGMEMOD

The AGMEMOD model seeks to reflect the heterogeneity of European agriculture through its modelling of agricultural commodity markets in all EU Member states. The AGMEMOD Partnership model is an econometric, dynamic, multi-product partial equilibrium model of the agricultural sector that allows to make projections and simulations in order to evaluate measures, programmes and policies in agriculture at the European Union (EU) level as well as at the Member States level (Chantreuil et al., 2012, AGMEMOD Consortium, 2010).

AGMEMOD is characterized by a great level of detail in the representation of crop and livestock products as well as their processing. The crop commodity coverage ranges from cereals and oilseeds with their derived products (oils and cakes) to potatoes, sugar beets and sugar. The livestock commodity coverage consists of cattle, beef, pigs, pigmeat, poultry, eggs and sheep and goats.

Furthermore, the model covers raw milk, whole milk, butter, skim milk powder, cream and other fresh milk products (AGMEMOD Consortium, 2010).

Over the next years AGMEMOD shall be extended to include also fishery and aquaculture commodity markets at the EU member state level. Therefore, we will estimate medium-term developments of the major fishery species (e.g. flat fish, ground fish, fresh water fish) and aquaculture commodity markets. The aim is to embed fishery and aquaculture commodity markets into agricultural crop and animal markets, on the supply side (e.g. fish meal for animal feed, grain use for aquaculture) and the demand side (e.g. fish for meat and dairy). This also includes capturing of competing claims of aquaculture on land use, which expands the economic oriented calculations to environmental aspects (e.g. emissions).

3.2.6 CAPRI

The CAPRI model (Common Agricultural Policy Regional Impact) is an agricultural sector model covering the whole of EU27, Norway and Western Balkans at regional level (250 regions) and global agricultural markets at country or country block level (CAPRI, 2012).

A special feature of CAPRI is that it links regional or even farm type models covering EU's agriculture with a complex global model for trade in agricultural products. CAPRI covers about 40 agricultural products, covering all of agriculture according to the definition of the Economic Accounts for Agriculture. On top, there is a limited number of processed products included (dairy, oils and cakes, bio-ethanol and bio-diesel and the related by-products) (CAPRI, 2012).

Simulation results cover areas cropped, herd sizes and income indicators for each agricultural activity and each region; prices, supply and demand positions at country level; environmental indicators (balances for N,P,K, emissions of ammonia, methane and N_2O, greenhouse gas inventories and life-cycle assessment of energy use in agriculture) at regional level; producer and consumer prices, supply and demand positions as well as bilateral trade flows with attached prices, transport costs and tariffs globally for each trade block (CAPRI, 2012).

The modelling system allows for spatial downscaling part to 1x1 km, which covers crop shares, yield, stocking densities, fertilizer application rates and the environmental indicators (CAPRI, 2012).

3.2.7 EFI-GTM

The European Forest Institute Global Trade Model (EFI-GTM) is a regionalized partial equilibrium model of the global forest sector with a special emphasis on Europe. The mathematical structure of the model is given in Kallio et al. (2004) and Moiseyev et al. (2011). The model has been used to analyse the economic impacts of accelerating forest growth in Europe (Solberg, B., et al., 2003), increased biodiversity protection in forestry (Kallio, M., et al., 2006), the impacts of reducing illegal logging (Moiseyev, A., et al., 2010), economic impacts of the Russian roundwood export tariffs (Solberg, B., 2010) and the potential contribution of forest biomass to the EU RES target (Moiseyev, A., et al., 2011, 2013).

This multi-regional multi-agent forest sector model is cast into a single mathematical programming problem with the economic interpretation that each region maximizes its social welfare function, which is the sum of consumer and producer surpluses less the transportation costs resulting from trade with the other regions. The model maximizes this surplus restricted by resources, capacity and budget constraints, as well as by possible barriers of trade. The model solution of this maximization thus simulates the market equilibrium outcomes assuming competitive markets. The dynamic changes from year to year are modelled by recursive programming. After each period, the data on market demand, timber supply and changes in production costs and available technologies, are updated. Thereafter, a new equilibrium is computed subject to the new demand and supply conditions, new technologies, and new capacities.

Each country in Europe is one region in the model. In addition 10 Asian, 2 North American, 3 Russian, 6 Latin American, 2 Oceanian, and 4 African regions are included making the system a global model linked through the transport costs between each region for all products. The base period data are defined for 58 world regions and 36 forest products, and for each region up to 3 types of technologies are defined, corresponding to low, high and average production costs. The wood supply in each region is characterized by equations that specify quantities of different wood categories as a function of real prices. The present version of the model includes four roundwood assortments: hardwood and softwood, each divided on pulpwood and saw logs. The supply functions are shifted inter-periodically, reflecting the changes in potential wood harvest. The EFISCEN model (Schelhaas et al. 2007), a forest resource projection model based on national forest inventory data, is providing European countries' information on the potential sustainable harvest level (Verkerk et al. 2011), which is used to limit the maximum harvest levels. The combination of EFISCEN with EFI/GTM allows us to model forest resource utilization and forest sector dynamics in a better way.

3.2.8 EFISCEN

The European Forest Information Scenario (EFISCEN) model is also developed by the European Forest Institute, and has been applied to the study of forest transition processes and the implications for carbon stocks and other environmental impacts (Schelhaas et al 2007). EFISCEN is an area-based matrix model that captures the change in forest characteristics over time, in terms of age and volume. The model has been parameterized and applied to most European regions, as well as to parts of Russia.

3.2.9 DYNA-CLUE

The CLUE model is based on the dynamic simulation of competition between land uses while the spatial allocation rules are based on a combination of empirical analysis of current land use patterns (Verburg et al., 2006a; Wassenaar et al., 2007), neighborhood characteristics (Verburg et al., 2004), and scenario specific decision rules (Overmars et al., 2007). The model typically downscales changes in demand for different land cover types to a high-resolution grid. The exact configuration of the model is case study specific while the overal modelling approach is generic and similar in various applications. The version of CLUE used for European level simulations (Dynamic Conversion of Land Use and its Effects model: Dyna-CLUE version 2.0) combines the top-down allocation of land use change to grid cells with a bottom-up determination of conversions for specific land use transitions (Verburg et al., 2009a). The spatial allocation rules are configured separately for each country to account for the country-specific context and land use preferences. For the entire European Union land cover changes are calculated for a regular raster of 1 x 1 km cells. The land requirements for the different land use types to be allocated by the model are specified at the national scale for each country within Europe separately. Changes in agricultural land area are based on the results of global multi-sector general equilibrium or partial equilibrium models, such as GTAP and CAPRI. Growth in built-up area is based on demographic development, immigration ratios and scenario-specific estimates of change in area used per person. Changes in natural vegetation are the result of both net changes in agricultural and built-up area and locally determined processes of re-growth of natural vegetation (Verburg and Overmars, 2009). After abandonment of agricultural land re-growth of natural vegetation is simulated as a function of the local growing conditions (soil and climate conditions), population and grazing pressure and management. The possibilities to convert natural vegetation into agricultural land or residential/industrial land depend on the location and the type of natural area. Path-dependent dynamics arise from the combination of top-down allocation of agricultural and urban demand and bottom-up simulation of the (re-)growth of natural vegetation.

3.2.10 CLU-Mondo

The CLU-MONDO model is a new, global and regional scale land use model that simulates, in contrast to other land cover change models, changes in land systems that are capable of providing various ecosystem goods and services at the same time. Land systems have characteristics such as crop production, livestock density, biomass and biodiversity. Therefore, the same production of ecosystem goods and services can be fulfilled by multiple combinations of land systems and the areas occupied by the different land systems are not straightforwardly determined by the regionally aggregated areas of land cover types. Consequently, the CLU-MONDO approach allows to directly respond to demands for ecosystem goods and services rather only to areas per land cover type. Since the uses of the land in large parts of the globe are essentially multifunctional, this approach is especially appropriate for applications where multiple service demands put claims on land resources.

The land systems classification use in this global model is provided by Van Asselen and Verburg, 2012 while the model is decribed by Van Asselen and Verburg, 2013 and applied for an analysis of land availability by Eitelberg et al., 2014.

Similar to the Dyna-CLUE model, the world-region level demands for the goods or services that put a pressure on the land systems are derived from an external global economic models or scenario projections.

3.3 Key elements of interest

Each of the models described above has a particular focus or “strength” that it was intended to exploit according to the research interests of the institute or group of researchers developing it. Even though these models do not capture all aspects of the bioeconomy that were shown in Figure 1, they do address a number of important aspects, nonetheless. The elements that are of key importance to monitoring the evolution of the knowledge-based bio-economy are the following:

- How the representation of key natural resources, such as land, water or forestry, are handled with respect to important production activities that fall within the bioeconomy.
- How the energy sector is handled, and the degree to which it plays a role in driving production across various sectors.

- How the chemical sector is represented – in terms of inputs into other production processes (such as fertilizers or pesticides in agriculture) or as final products for the household consumer.

We will explore these areas of interest in more detail, in the following sections.

4 Operational linkages between models

Given our description of the various analytical tools that we have at our disposal – we now proceed to discuss where the main entry points for linkage are among them. Not all linkages are "two-way", as we shall see – and not all aspects of the models can be exploited in this interaction. It will become clear to the reader why the kind of proposed model linkages are complex and often not carried out within the scope of many analytical exercises. Given the limits to the scope and breadth of this study, they will not be attempted here, either.

4.1 Main entry-points for linkage

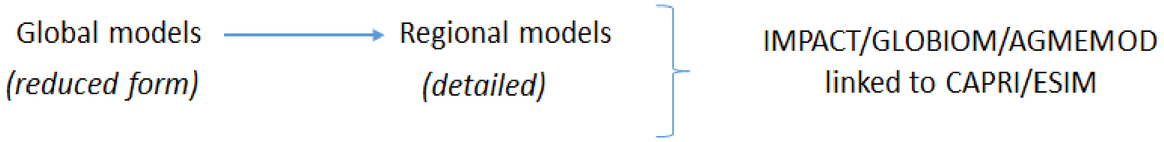
Now we will break down the key types of linkage that are possible with the analytical tools that we have at our disposal for this study. Simply put – they are prices or quantities. Given that many of the models that we are considering for the systems analysis of the bioeconomy are economic in nature – they will be amenable to using prices as a point of interface. Other models are driven more by process or biophysical relationships – therefore, they will need to rely more on quantities to "speak" to each other. These are described in more detail below.

4.1.1 Prices

Given the fact that many of our analytical tools are economic models – prices remain the primary "language" through which they communicate with each other. Most models solve for a fixed-point equilibrium which satisfies a number of reduced form equations that represent cost-minimizing, utility- or profit-maximizing behaviour of stylized actors, firms or representative agents within the economy. Some make the optimization of a welfare criterion (subject to constraints and structural relationships) more explicit, and generate "shadow" prices that reflect the scarcity values associated with a constrained or limited resource. The main types of prices that we would consider are: (1) producer prices relative to firms; (2) consumer prices that are relevant to households; and (3) factor prices that relate to the marketed inputs of production that are tradable (e.g. fertilizer) or non-tradable (e.g. land). Some models might hold certain prices constant – such as in PE models when some markets are ignored, or in regional models, where the "rest-of-the-world" (and the markets within them) are assumed to have fixed prices. In such a case – those fixed and exogenous prices can be 'shifted' by the flexible and endogenous prices that could come from other models. Such as a CGE model giving prices changes to a PE model, or a world model imposing border price changes on a regional model.

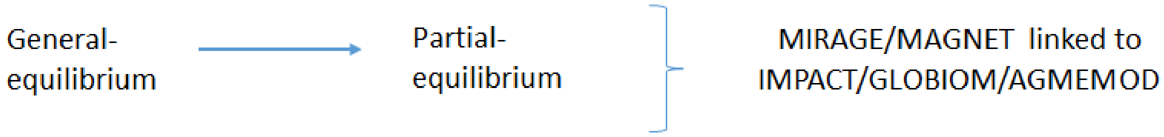
Prices allow the analytical tools to represent socio-economic welfare changes (or impacts) that a non-economic model would not be able to capture. In cases where a model accounts for the incomes (and even total asset values) of consumer households – the changes in price can be used to change the purchasing power of the economic agents and their overall economic well-being. The presence of prices also enables the flow of payments, revenues or transfers within the economic network of actors to be represented, and can provide useful points of comparison with which to judge the compatibility of the modelling tools, in terms of their economic, market-driven responses.

In terms of producer and consumer prices – the regional models can take the international market prices generated by the global models, and use those to determine how the border and internal market prices evolve at the local and regional level. An example of this is shown in the schematic below



where the global models can be either PE or GE in nature.

In terms of factor prices, the GE models tend to model them more completely than the PE models – and can therefore provide the "drivers" for changing those prices that the PE models can respond to. This is reflected in the schematic below.



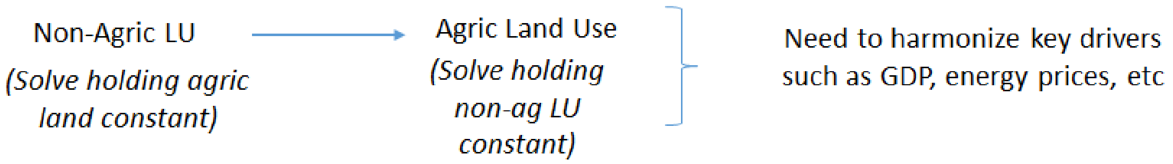
Some models will be more explicit in how they price the factors of production – such as in GE models – whereas others may not be. The GLOBIOM model considers a shadow prices for some non-traded factors such as land, whereas the GE models will typically have an explicit value for land. Within the CLUE model, there are no land prices. EFI-GTM considers prices for goods, but not for land. For sectors such as energy, which the CGE models might handle with more detail compared to the PE models (which might only consider the price of biofuels, for example) – there would also have to be some effort to harmonize assumptions. This will be discussed in more detail in section 4.2.

4.1.2 Physical quantities

The secondary "language" through which the analytical tools can communicate is that of physical quantities that represent produced and consumed goods, as well as the factors of production that are required. Such quantities – production, consumption, trade, water volumes, land areas, etc – can also be used as 'shifters' that allow the endogenous results of one model to drive changes in the exogenous components of another model.

In contrast to prices – physical quantities can be generated by both economic as well as more engineering-based models, as they can represent the outcomes of behaviour or of biophysical processes that occur outside the human domain (but which can still be influenced by it). An example could be the yield levels coming from an agronomic crop growth model defining the frontier (or population) of production possibilities within which the price-responsive supply of an economic model must remain. Due to computational difficulties, it's not common to find that the quantities derived from the process and economic model are calculated simultaneously – whereas it is more often the case that a derived, reduced form 'schedule' of quantity possibilities are summarized from one model, in order to define the range of behaviour that the other model can react to.

The linkages that might happen through simulated quantities might require that the endogenous outputs coming from one model are directly imposed upon another – either in real-time (if simultaneous solution is possible), or through iteratively constraining one model to the quantities simulated by the other. This type of linkage is shown, below, in the case of agricultural and non-agricultural land use



This is clearly an area where the forest-focused models (EFI/GTM and EFISCEN) can communicate with the land use components of models that include the forestry sector such as MAGNET, MIRAGE and GLOBIOM. We will talk about this further in the next section.

Water is also a physical quantity that is handled by some of the models used in this research consortium (GLOBIOM, IMPACT and GTAP-W based versions of MIRAGE or MAGNET). Given the vastly different ways in which it is handled within those models, though, there is a challenge in coming to some broad agreement as to the trends of use – which we will also discuss in the next section.

Aside from the price of energy, there is also a 'volume' of energy consumed or produced that could serve as a point of linkage between the models – especially those that handle the biofuels sector. This will be discussed in more detail in the following section.

4.2 Key sectors of interest

Given our interest in representing the performance and growth of the bioeconomy, we focus our attention on a set of sectors that provide the best starting point from which the various analytical tools can have operational linkages between them.

4.2.1 Energy

Energy represents a key input to industrial (or intensive agricultural) production, although it is often not modelled explicitly as a sector. The GE models are probably in the best position to evaluate the energy dimensions of the bio-economy, given that there is a GTAP-E database in which the energy usages and requirements within the wider economy are brought out.

For PE models (such as IMPACT and GLOBIOM), the production of biofuels represents a type of energy supply (to the transportation sector), and is explicitly modelled in terms of its market supply, demand and trade dimensions. The demand for biofuels is related to the price of fossil-based fuels, which is not modelled explicitly in those models. These could be better handled by economy-wide GE models that can take advantage of the GTAP-E database. IMPACT and GLOBIOM could, however, capture the use of ethanol by-products such as dried distillers grains and solubles (DDGS) in the livestock sector – which is an important feature of the bioeconomy, where better use is made of the co-products from any industrial process.

In order to create a strong linkage between the various models that handle energy – especially that embodied in biofuels – there would have to be a close agreement between certain drivers of change. The most important would be the trend of oil prices that would be assumed in the various models. Given the strong degree of market power that is exerted in the oil market by OPEC, it is difficult to endogenously project the volumes of oil produced and the prices with any degree of confidence. However, given a projected price level for oil, it would be possible to agree upon the elasticities of demand that correspond to different oil-consuming sectors. The price of oil and fossil-based fuels is a key determinant of biofuels production and consumption, given that it is blended as a complement (or even used as a substitute, in some cases) – depending on the prevailing country policy. Therefore, the various models that handle biofuels could agree upon the policy regimes and how they might change over time, barriers to trade in biofuel products, and seek to agree upon the trends in biofuel production and consumption that might be plausible over time. As is the case with other kinds of model linkage, this linkage would have to be relatively 'soft' and require the careful tuning of various elasticities of demand and substitution. Given that the CGE models (using GTAP-E and its variants) have more details on energy, compared to the PE models like GLOBIOM and IMPACT – certain trends, such as transportation energy demand, and fossil fuel prices can be imposed by the CGE models upon the PE models, in order to achieve harmonization more quickly.

In the case of energy from forest and forest industries' residues, the EFI-GTM model is in the best position to capture those aspects. It can model competition between fossil fuels (such as coal and natural gas) and wood biomass for electricity and heat production (Moiseyev, A., et al., 2013).

4.2.2 Chemicals

The economy-wide GE models (MIRAGE, MAGNET) do a better job in representing the behaviour of the chemical sector, given its importance in the industrial sector. Nonetheless, the PE models can influence the use of chemicals like fertilizer by driving up agricultural supply, and accounting for the fertilizer requirements per unit of productivity. In the case of GLOBIOM, there are explicit agronomic crop growth models that allow application of fertilizer to directly affect agricultural productivity. Within IMPACT, there are productivity functions that depend on (exogenously-held) fertilizer prices – so the results from the GE models can directly affect how these prices could change over time.

Within the context of the MEV-II project (Macro-economic outlook of sustainable energy and biorenewables innovations), both LEI and Utrecht University are working together on creating better linkages between the chemicals sector and the modeling of energy. Utrecht University has developed the chemical sector module of the bottom-up linear optimization model MARKAL-NL-UU. This sector interacts with the electricity/heat and transport fuel modules of MARKAL-NL-UU, and further work is anticipated to provide a 'soft link' between this modeling framework and the MAGNET model. The regional scope of this work is the Netherlands and the timeframe of analysis is up to 2030, and further research outputs are forthcoming.

The work of Daioglou et al (2014) brings greater attention on the use of fossil-based resources for non-energy-focused uses within the chemicals sector, and represents an important step forward in understanding how fossil fuels have been used for the bulk production of chemicals. This work involves models that are not within the toolbox of this research consortium, but points to important directions for further research. It takes the energy modules that have been developed within integrated assessment models – such as the IMAGE model – and explores how high-value chemicals, ammonia, methanol and other refinery products can be obtained from the fossil-fuel sector.

4.2.3 Fisheries

There are relatively few models that handle the fishery sector in great detail – especially as it relates to both capture fisheries and aquaculture. These two types of fish production systems are quite different – one based on the harvest of marine and inland resources, while the other is a more intensive system that requires feed and more intensive use of labour (e.g. in managing disease) -- and require different modelling approaches. The underlying ecological dynamics of fish populations that are harvested within capture fisheries must be modelled with explicit ecosystem models that capture the interaction of fish populations with their natural environment and the predator-prey dynamics between species at different trophic levels. There are models that have been developed to capture these types of dynamics – such as the EcoPath with EcoSim (EwE) suite of models that have been used in a number of environmental studies (Christensen and Walters, 2004a, 2004b).

Aquaculture, on the other hand, is a production system that bears closer resemblance to livestock-based agriculture – in which the management of feed and disease are the key components of the system. The more intensive use inputs also requires a more intensive use of labor and technology, which enables the modelling of the aquaculture sector to more closely resemble that of crop and livestock-based activities in the rest of agriculture. In particular, the way in which fishmeal and fishoil are produced is quite similar to how the agriculture-based oilseed sector is handled – given that a feedstock (i.e. whole fish) must be crushed and reduced into the components of oil and meal that are used for human consumption and animal feed. The schematic below shows how these sectors can be linked explicitly (Figure 3).

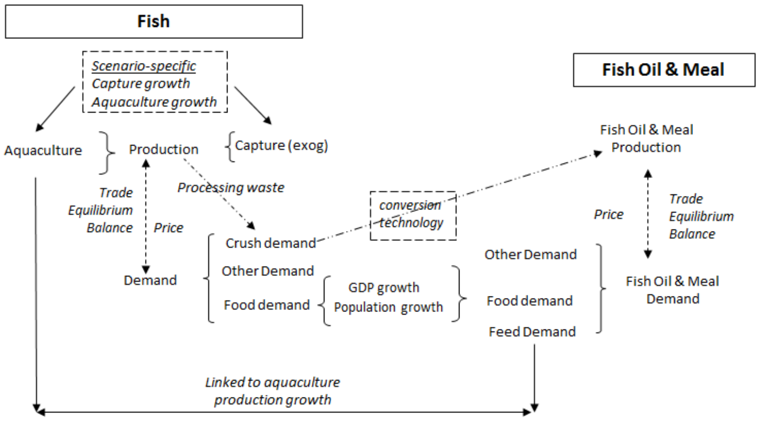


Figure 3: Schematic Linking Fish with Fishmeal and Fishoil in the IMPACT model

The modelling work that IFPRI did for the recent World Bank publication on the outlook for fisheries and fish-based products to 2030 incorporates this framework, but only endogenized the aquaculture sector – leaving the capture fishery production to be represented by an exogenously-specified trend (Msangi et al 2013). A linkage between an ecosystems-based modelling framework of capture fishery production could be made to improve this body of work – but has not yet been carried out.

One of the key links to the bio-economy is captured in the use of waste products from fishery processing as a feedstock for fishmeal and fishoil, rather than using whole fish that are obtained from capture fisheries. By making better use of waste products generated within the value chain of the fisheries industry, the depletion of live fish species from the marine ecosystem can be reduced, as well as the use of energy that is embodies in harvesting live fish from the open ocean. This dual environmental benefit is analogous to the use of co-products from other bio-based processes for feed – such as the dried distillers grains and solubles (DDGS) that comes from biofuels manufacturing.

4.2.4 Land

Given that land is such a key resource for both agricultural and non-agricultural sectors, the way in which it is linked between analytical tools can provide very useful insight into the environmental state underlying the bioeconomy. The quantity of land 'demanded' by a sector like agriculture, for example, can be provided by a PE model, and a land use model like CLUE can simulate where the room for expansion can be found.

Given the very different way in which the allocation mechanisms for land are done within the GE model and the CLUE models, it is not entirely clear how the quantities of land can be linked between them. The GE models would tend to allocate land across different activities according to relative prices of (or net returns per unit) land, whereas the mechanism within CLUE is more rule-based. A more systematic comparison and study of these mechanisms is needed to better understand the implications of these differences.

The forestry sector, in particular, offers some promising avenues for linkage of land use trends, given that several of the models in our consortium handle this sector explicitly. The details on linkage are discussed in a later sub-section.

An example of model linkages including land resources and the agricultural and forest sectors was implemented in the VOLANTE project, where land use change quantified in CLUE was driven by agricultural resource use calculated by the CAPRI model. The resulting change in land availability was then used in EFISCEN to change the forest area (and consequent wood availability) as an input to the EFI-GTM model (Lotze-Campen et al. 2013).

4.2.5 Water

In the case of water, the volume of water needed to achieve a certain level of productivity (for crops or for other commodities) can be specified within a rule or technical relationship that can be imposed on the production per unit of an economic model. The total amount of water that is available for productive use can be either specified exogenously to a model, or even modelled explicitly within an engineering-type analytical framework. That is the case with the IMPACT model, where a coupled inter-sectoral water allocation model determines how much is available for irrigated production in various regions.

There are a number of GE models which try and account for water explicitly – such as in the GTAP-W family of models that have been recently developed. In GTAP-W, water is added into the model as a factor of production, and accounts for differences in agricultural productivity, as well as service as an input into other sectors (REF). In principle, either MAGNET or MIRAGE could make use of GTAP-W to include water as an explicit component. In the case of the GLOBIOM model, the agronomic crop model (EPIC) that determine grid-level production levels also take the moisture (i.e. water) conditions into account, even though the management of water (and its allocation across sectors) is not made explicit.

In IMPACT, there is a hydrological model component that carries out an inter-sectoral allocation of surface water between the industrial, residential and agricultural sector, and which looks at the overall consumptive use and depletion of water at an aggregate basin-level. This inter-sectoral allocation model for water is linked to the agricultural market-equilibrium model in such a way that increasing demands for water from the industrial, residential or livestock sectors will reduce the availability of water to agricultural crops – thereby causing a decrease in crop yield, according to the severity of the deficit (Rosegrant et al 2002).

In order to 'link' these models, in terms of their water usage, a common hydrological scenario would have to be derived and agreed upon – such that that aggregate amount of water that is available for consumptive use by the various sectors is consistent across all models and a given climate scenario. This physical quantity of water would have to be specified in terms of the surface water runoff that is free-flowing ('blue' water), as well as the water that is embedded in the soil moisture profile and is represented in the overall evapo-transpirative consumption of water in vegetative cover (the 'green' water). The GLOBIOM would use this 'green' water in its calculations of crop productivity that are conditioned on the soil-water balance, whereas the allocations of water to agriculture and other sectors that are considered by the GTAP-W based versions of MAGNET or MIRAGE and the IMPACT model would have to roughly match in magnitude and shares of allocation. Given that the mechanisms for determining the inter-sectoral allocation of water resources would be very different in the CGE models versus a partial equilibrium model like IMPACT, the agreement would – again – not be exact between the models, but might broadly agree in terms of longer-term trends of relative consumptive use of water in the various sectors. Therefore a lot of 'tuning' would need to be done, in order to get this kind of broad agreement in water use trends.

4.2.6 Forestry

The EFI-GTM model provides a comprehensive framework for understanding how the forest sector operates, and has details on forestry activities that are handled at a more aggregate level in the GE models that incorporate land (through the GTAP-AEZ based framework). The linkage with the EFISCEN model allows simulating policy and management changes affecting forest resource utilization, under consideration of environmental constraints of biomass availability (Verkerk et al. 2011), and with the possibility to also evaluate the resource management impacts on ecosystem service provisioning (Verkerk et al. 2014). EFI-GTM uses the biomass supply potentials from EFISCEN and calculates the realised demand using the PE optimization and the allocation of the biomass to both material use and energy use in the forest-based and energy sectors. Newly evolving biorefinery products (e.g. biofuels) are not usually included, except in some specific model cases, such as the Finnish forest and energy sector partial equilibrium model FinFEP, in which the second generation biodiesel production in integrated pulp and paper mills is analysed (Kangas et al. 2011). More generally, the simplified power and heat energy sector starts to be a part of the new forest sector PE models, such as EFI-GTM model (Moiseyev et al., 2013).

There is also a known limitation of the PE models based on parameters generated by econometric equations estimated from past data and market structures. Especially, it has been shown, that the current forest sector models fail to take into account the structural changes in paper markets, due to which the past data and current paper demand equations cannot track the recent changes, not to mention project the future developments (Hurmekoski & Hetemäki 2013). This is leading to an overestimate of the forest products demand, which is used as one of the main inputs for the forest sector's PE models. GLOBIOM pays quite a bit of attention to forestry in the way that it handles land allocations between forestry and other activities like crops and livestock.

Providing an explicit link across the various models that handle forestry is somewhat challenging. Since some of these models are market-equilibrium based models (MAGNET, MIRAGE, GLOBIOM and EFI/GTM), whereas EFISCEN is not – as was depicted in Figure 1 – the mechanism for linkage has to be somewhat indirect, by necessity. In essence, the EFI/GTM and EFISCEN models have to be coupled first – such that they 'agree' on the expanse and utilization of forest land that is plausible under various economic drivers of change. The combined result from this 'stage one' harmonization would then be harmonized with the other partial- and general-equilibrium models that have a forestry sector – GLOBIOM, MAGNET and MIRAGE. Importantly, the principal underlying drivers of these models would have to agree – such as GDP and population growth. Any harvest, consumption and price trends for forest products would have to be compared and matched in some way – even though the degree of resolution on forest products will differ considerably between them, with the combined EFI/GTM-EFISCEN models having the most detail as to types of forest products and co-products. Given this challenge, it might not be possible to reach full harmonization on all aspects of how the forest sector behaves in these models – given the wide methodological difference in how they are handled. However some broad agreement on certain aspects – such as the overall share of consumption or traded value of forest products vis-à-vis all other commodities – might be possible.

In the VOLANTE project, one-way linkages were realised so that GE models (Remind/MagPie and MAGNET) provided drivers such as economic growth or technology change to PE models (CAPRI and EFI-GTM) and calculated changes in agricultural production were used in CLUE to project land use change, which affected forest area in EFISCEN and consequently the wood harvesting potentials in EFI-GTM (Lotze-Campen et al. 2013). Feedbacks were only considered between supply potentials in EFISCEN and realised wood demand from EFI-GTM. Possible feedbacks to the GE models were considered for the bioenergy demand, but finally not implemented.

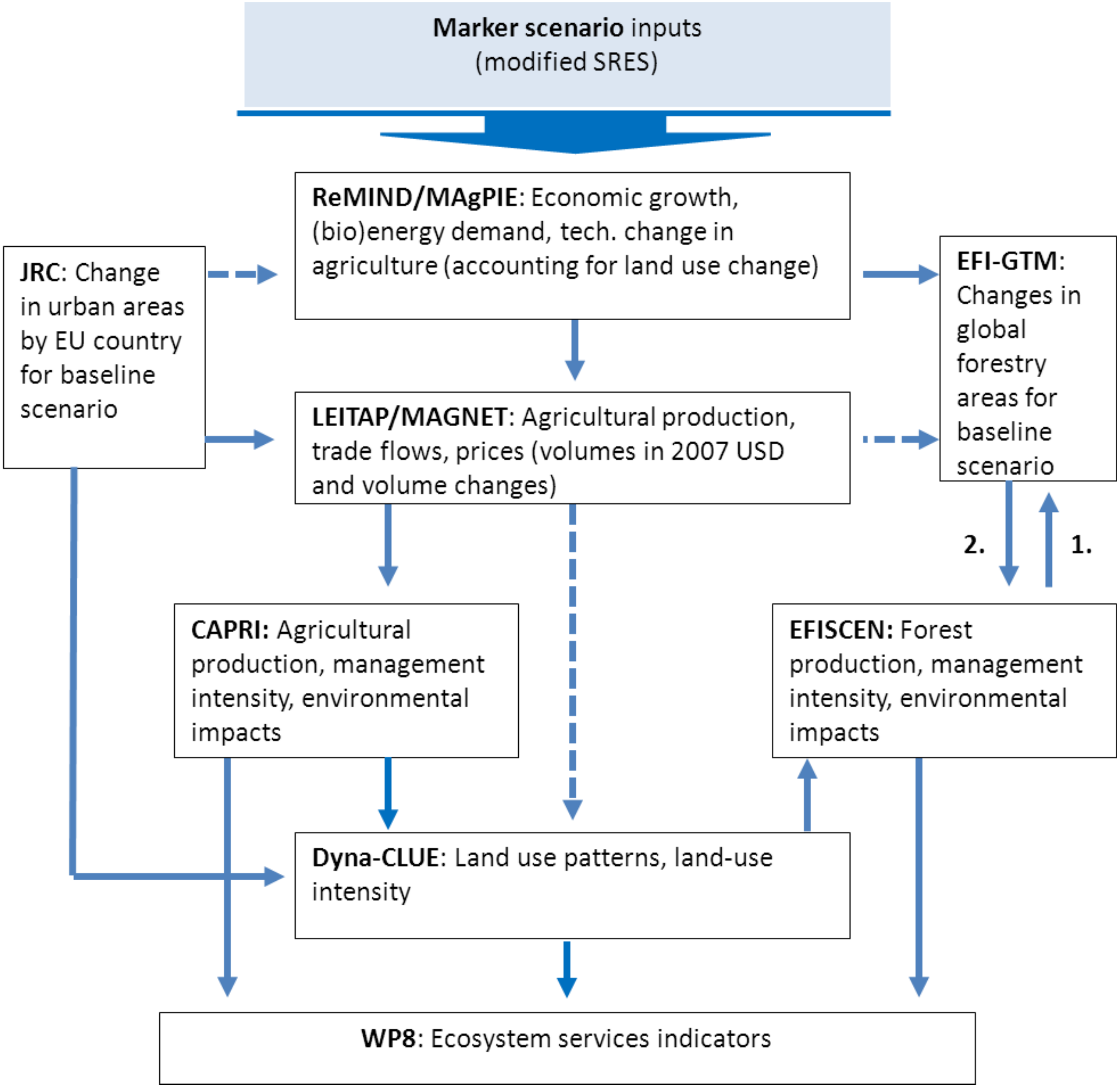


Figure 4: Model linkages realised in the VOLANTE project (Lotze-Campen et al. 2013) to capture scenario impacts on land use and their effects of ecosystem service provisioning.

4.3 Critical methodological challenges to modeling

4.3.1 Inclusion of environmental quality aspects

In our treatment of key environmental components such as land use and water – we have neglected to mention some important aspects that relate to environmental quality, health and well-being – such as soil quality, water quality and ecosystem health and functioning. Most of the models that are included in our consortium focus on the *quantities* of goods produced, consumed or traded, but do not go into the details of quality – which is important, when one considers important issues of environmental well-being. There are some aspects of quality that are handled, however, in some of the models that look closely at land use. The CGE models that might use the GTAP-AEZ database on land productivity can capture some aspects of land quality in their modelling – since the different agro-ecological zone (AEZ) classifications capture the types of agricultural land and their relative productivity for various types of agricultural crops. But these models cannot explicitly model the deterioration of land quality that might result from sub-optimal land management or agricultural practices – since the AEZ classifications are fixed and cannot shift endogenously according to the simulated model outcomes. In order for this to happen a new AEZ map would have to be re-drawn at pre-defined periods, such that the past history of production results in a different distribution of suitabilities. But this is a tedious and computationally un-manageable process, given that the entire GTAP database of activities that are delineated across these AEZ classifications would have to be re-drawn, re-initialized and re-calibrated to fit. The high level of aggregation that the GTAP based models operate at, relative to the scale at which degradation of soil and land quality would actually happen would also pose a problem of resolution that would be difficult to reconcile meaningfully.

The GLOBIOM model, which uses the agronomic EPIC model as an analytical calculator of agricultural crop productivity at the pixel-level can take some aspects of soil quality into account – such as soil organic matter content, which has important implications for the water-holding capacity of soils, and the availability of nutrients to the crop. But capturing the feedback of various agricultural practices on soil quality over time would, again, have to be done in a recursive and computationally intensive manner, for all the thousands of grid points that the production map of GLOBIOM covers, globally. In contrast to the GTAP-AEZ-based models, which simulate production at a highly aggregate level – the grid-level calculations of GLOBIOM are better suited to capturing the realities of degradation at a more localized scale. But the computational burden of doing so in a dynamically-recursive way for the many grid points it has to consider, is the main challenge.

Water quality is also another aspect that would be important to capture – as it affects both agricultural and non-agricultural types of water use. In the case of agriculture, salinity is the most important dimension of water quality that would have a direct impact on production. The IMPACT model only considers water quantity as a constraint to crop productivity, and is not able to account for salinity effects. The GLOBIOM model, which uses an agronomic model that might offer some avenues for capturing salinity-driven yield effects, does not currently look into this aspect of water quality. The impact of agricultural fertilizer use on water quality would also be an important aspect of environmental quality to capture – but is not addressed by any of the models within the consortium. The most important aspect of this effect would be the run off of nitrogen and phosphate based fertilizer residues into surface waters, which presents a problem of nitrification and depletion of biological oxygen demand (BOD) for fish and other water-borne life in lakes and rivers – and the proliferation of algae blooms in coastal areas. This level of environmental detail requires the models to capture the routing of water over the landscape, in order to represent the aggregate effect of these cumulative nutrient loadings on specific water bodies.

Relating to land use – one of the most important aspects of environmental quality and ecosystem health is the area available for habitat, and the degree to which biological diversity (i.e. biodiversity) is preserved across the landscape. Although several models in the consortium look at land use change in terms of the *quantities* of land converted from natural to managed cover, and the physical extent of that conversion – none of them consider the impacts on habitat or biodiversity across the landscape. This is an important aspect of sustainability that would need to be considered in the study of a knowledge-based bioeconomy.

There are relatively few modelling efforts that have been able to capture some of these aspects of environmental quality adequately. One example, however, is the GEO-4 assessment of UNEP, which brought together a detailed quantitative component to evaluate the future evolution of key indicators of environmental and human well-being across various storyline-based scenarios (UNEP 2007). The Global Environmental Outlook (GEO) is a periodic global assessment that is carried out by a particular agency of the UN system – the UN Environment Program (UNEP) – as a way of mobilizing awareness around the environmental issues they advocate for. The 4th GEO assessment (UNEP 2007), in particular, bore a strong resemblance in its structure to the earlier Millennium Ecosystem Assessment (MEA, 2005) – in that it used a set of storylines or alternative futures to mobilize creative discussion among key stakeholder groups about the various drivers of socio-economic and policy influence that impact key sectors of the environment (land, water, biodiversity, etc).

Similar to the MEA – the GEO-4 assessment engaged research teams and stakeholders to think about the key storylines (Policy First, Markets First, Security First and Sustainability First) – and how they influence future socio-economic and environmental outcomes in both qualitative and quantitative terms. Unlike the one-time MEA, however, the GEO assessment is meant to be an ongoing and flagship product of UNEP that helps to bring attention to the state of the environment, and the important drivers affecting its evolution.

The quantitative framework that was employed within the GEO-4 assessment linked a number of quantitative, forward-looking models together, in order to represent the critical linkages between socio-economic growth, agricultural expansion, energy consumption and its linkages to climate outcomes, and the resulting implications for land and marine ecosystem health. Figure 5, below, shows the critical linkages between the various modeling components, and the important indicators of environmental and socio-economic well-being that were measured.

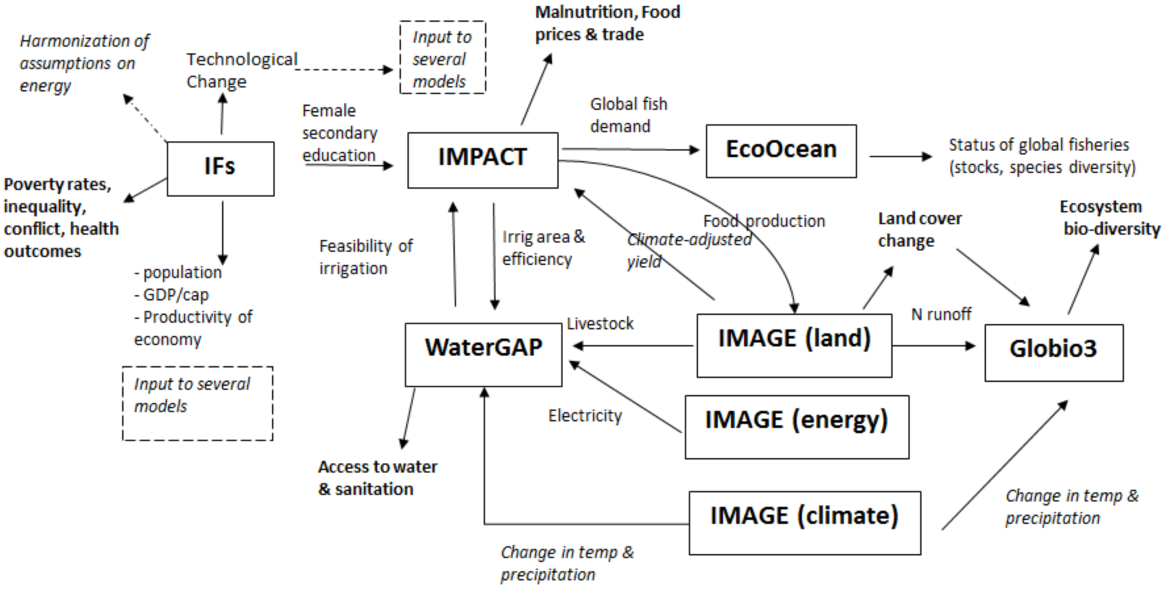


Figure 5: Key modeling components of the GEO-4 assessment

Key among these environmental indicators were those which measured water quality impacts through Nitrogen runoff (coming from the IMAGE model), the species diversity in ocean-based fish populations (with the EcoOcean model), and the change in species biodiversity captured by the GLOBIO3 model.

The International Futures (IFs) model was the main economic ‘engine’ that drove many of the demographic and economic growth dynamics that were used as inputs into the other models – such as population growth (by sex and age cohort), GDP growth, and levels of educational attainment and access to sanitation. The storylines of the GEO-4 assessment were used to define specific trajectories of the key socio-economic trends and policy decisions –particularly with respect to trade policy, technological innovation, environmental protection, domestic social policy and geo-political cooperation, and are described in Table 1 below.

Table 1: Summary descriptions of scenarios for GEO-4 assessment

Scenarios	Key characteristics
Markets First	Strong belief in the ability of markets to deliver economic and environmental benefits. High degrees of privatization of services, R&D dominated by private sector and more emphasis on FDI rather than ODA. Greater economic cooperation through regional bodies. Formal environmental protection grows slowly and fossil fuels continue to dominate. Phasing out of subsidies
Policy First	Highly centralized approach to governing and achieving a balance between strong economic growth, social benefits and low environmental impacts. Coordination across governments to tackle challenging problems of development, more holistic approach to governance, greater emphasis on environmental stewardship and less faith in the ability of markets to meet goals. Strong leadership by national and multi-national governing bodies (UN, etc)
Security First	Strong emphasis on security to the exclusion of other goals. Less freedom of movement (migration, sharing of ideas) and more protectionism (esp trade). Continued conflict reduces resources available for human development, R&D. ODA and FDI is decreased and subject to more conditionality. Weak or non-existent social safety-nets. Little environmental governance, and more corruption in government and less cooperation b/w govt and civil society
Sustainability First	All actors follow through on development pledges and act in concert to address social and environmental problems. More initiatives from private sector and greater coordination and support from government. Improved environmental governance which seeks complementarity between social & environmental goals. Increased public & private investments across the board. Increased awareness for the need to reduce pressures on resources

Based upon these storylines, a trajectory of future socio-economic and environmental change was simulated in a way that reflected the underlying assumptions of these storylines – as was also done for the MEA study. The storyline that would correspond most closely to the vision of a knowledge-based bio-economy is that of “Sustainability First”, in which there is an underlying assumption that environmental governance evolves to reflect both the complementarities as well as the competition between social and environmental goals. In the area of energy and water provision, for example, there are more efforts to balance the reduction of overall resource use with the need to address water stress, greater access to energy and the reduction of poverty. Towards that end, there are increased public investments in water infrastructure and the development of energy technologies that are more environment-friendly (UNEP 2007).

The quantitative framework that was used in GEO-4 was quite elaborate, and used a range of models that exceeds what is currently available in our consortium – given that we do not cover the details of fisheries, water and the important energy-land-climate interactions that can be captured within an integrated assessment model like IMAGE. A detailed description of the various models that were used is given in Table 2, below.

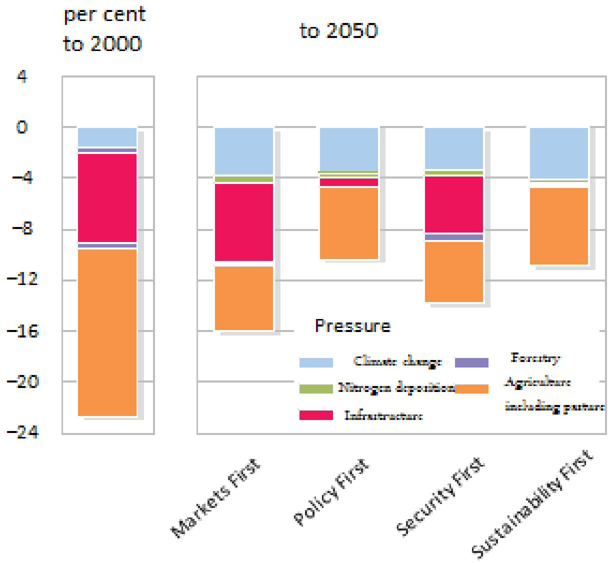
Table 2: Summary description of models used in GEO-4 assessment

Model	Key characteristics
International Futures (IFs)	The International Futures (IFs) model is a foresight tool that has been developed by the Pardee Center for International Futures for carrying out forward-looking assessments of socio-economic change and their implications (and feedbacks with) the national and geo-political economy. It has been used to address questions surrounding investments in health, education and other key sectors, as well as to provide a variety of useful indicators on population, poverty, economic growth, conflict, hunger and human well-being resulting from alternative policy pathways. At its core is a general-equilibrium modeling framework, linked to a detailed demographics module, as well as to other sector sub-modules through a systems dynamics framework
IMPACT	The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) is a global, partial-equilibrium, multi-market model of the agricultural sector, that has been used by IFPRI (the International Food Policy Research Institute) to make future projections of agricultural production, demand and trade – as well as the implications of agricultural (and non-ag) investments on malnutrition levels. Agricultural production is linked to a detailed water allocation model that determines the availability of water for irrigation and livestock.
IMAGE	The Integrated Model to Assess the Global Environment (IMAGE) was developed by the Environmental Assessment Agency of the Netherlands to provide global assessments of linked atmospheric and terrestrial systems, and the feedbacks between human activity in the agricultural and energy domain on climate. It has been applied in a number of global climate assessments and contains detailed biophysical modules that model climate dynamics, land use change, and GHG emissions from agriculture and the energy sector.
WaterGAP	The WaterGAP (Water – a Global Assessment and Prognosis) model has been developed by the Center for Environmental Systems and Research at the University of Kassel to analyze global scenarios of water demand within the context of climate-driven constraints on supply. The model accounts in detail for hydrology and water infrastructure in simulating the availability and access to water for residential, industrial, agricultural and environmental uses. The model is designed to link with other models of land use change, climate dynamics and economic growth in order to provide a more integrated perspective
EcoOcean	The EcoOcean model represents a combination of detailed biophysical models that represent the population dynamics of fish at various trophic levels of the ocean and their interaction with the environment, in order to give a complete picture of how key global marine ecosystems will evolve over time. The EcoOcean modeling suite links fishing effort to the harvest and landings of fish, and their subsequent implications on the underlying biological population dynamics. It has been used in a number of environmental assessments to assess the impact of over-fishing as well as the implications of climate-driven ocean temperature change on future marine ecosystem health.

Globio3	The Globio3 model is a reduced-form simulation model that links the changes in natural species habitat (as a result of land conversion and environmental degradation) to changes in species abundance and diversity. This has been used in various assessments of species conservation.

In particular, we can look at the way in which biodiversity impacts were represented in GEO-4, as is shown in Figure 6, below, which captures the outputs of the GLOBIO3 model for the Africa region.

Figure 6: Historical and future declines in mean species abundance (MSA) in Africa under the GEO-4 scenarios



Note: GLOBIO modeling results.

Source: UNEP (2007)

As would be expected, the negative impacts on biodiversity – measured as a decrease in the index of mean species abundance – is among the lowest in the *Sustainability-First* scenario, compared to other scenarios like *Markets-First* which is mostly driven by economic forces, with little regard for environmental outcomes.

While it is not possible to bring this degree of modelling to this current study, given the resources available – it is useful to consider the example of the GEO-4 assessment in thinking about future extensions to our analytical framework. Given that the GLOBIO3 model gives a very aggregate and crude measure of biodiversity impacts – there is a great deal of improvement that can be done through taking a more detailed look at species impact on a landscape level. These approaches require considerable amounts of data and ground-truthing, in order to be able to say more specific things about how the loss of habitat from land cover change affects the viability of different insect or animal species, and what the wider ecosystem impacts are likely to be.

4.3.2 Balancing between equilibrium and non-equilibrium processes

Within our modelling consortium, there is a mix of market equilibrium-focused models and those models which are simulation-based, and do not consider prices as a mechanism for guiding behavioural response. While this does not present a problem to our study – since it reflects the reality that some processes are economic in nature while others are driven by biophysical relationships and interactions – it does represent a challenge in how model linkages are done. As was discussed in section 4.1, where the various 'entry points' for linkage were mentioned – prices and quantities are the two types of 'media' through which the models can communicate. All of the models – whether they are market equilibrium-based or simulation-based – have a representation of quantities of goods produced or consumed. Therefore, we can always achieve a linkage between them in terms of trying to match how the quantity-based indicators of land use, production, input use, etc are projected over time. A harmonization according to price changes, however, cannot be done across all of the models, and might limit the extent to which behavioural dimensions of agents can be linked – especially if we think that certain aspects of behaviour (such as consumption) are driven by changes in prices.

Given the complexity of the global economy and biosphere, however, it would be unrealistic to expect that a total harmonization of models would be possible, since each component of the global economy or eco-sphere requires a certain degree of specialization in the models that are trying to capture it. If one wishes to capture important aspects of environmental quality, as was mentioned in the previous sub-section – it would be necessary to consider simulation-based models that can capture water quality degradation, biodiversity loss, air pollution and other biophysical aspects that do not have an economics-based component that directly governs its evolution over time.

In order to manage this tension between capturing equilibrium and non-market equilibrium effects, one has to simplify the modelling components within either model family so that they would be able to have common quantity-based indicators through which linkage and an (eventual) harmonization of model-based outcomes can be achieved.

4.3.3 Capturing important dimensions of social sustainability

Within our modelling framework, there are a number of components that capture the socio-economic impacts of the fossil- and bio-based economies on consumers of agricultural and non-agricultural products, as well as on households in general. These impacts are mostly captured through the transmission of price effects through market-based mechanisms – such as through wage markets or product markets. Changes in the demand and supply of labour to various sectors of the economy (fossil- or bio-based) are translated into changes in wages that accrue to those households which supply workers to the wider economy. Those wage changes affect the overall income of those households and their ability to afford the purchases of necessary consumption items – whose prices are also determined within the same market-based mechanism. Those changes in income, expenditure and consumption are one aspect of socio-economic impact that is relevant – but there might be other non-market based aspects that are also of importance.

If we take into account the value of a healthy and well-functioning ecosystem, and what it provides in terms of habitat and recreational value for those who enjoy being in a clean, outdoor environment – then we have to consider aspects of human well-being that cannot be directly priced.

If the evolution of the bio-based economy is to have some impacts on environmental quality and, therefore, the recreational value that human populations derive from the landscape – then some means of capturing these welfare effects have to be found. The work done on forestry with the EFI-GTM model has taken aspects of recreational value into account (Kallio et al 2006), but this has not been done as much for other sectors. This is one aspect of 'quality' that needs to be accounted for in future research, in order to better understand how social sustainability can be enhanced in the evolution of the bio-based economy.

Other aspects of human well-being – such as poverty and undernutrition – are also important indicators of social sustainability that the models within our research consortium have some ability to address. The household micro-simulation modules of the MAGNET and MIRAGE models are able to capture the poverty impacts arising from changes in policy regimes – such as is often done for studies looking at the welfare impacts of trade policies (Bouet and Laborde 2010). The work that IFPRI has done on impacts relating to climate change or other interventions on child malnutrition and other indicators of hunger in the general population, is also indicative of what can be done to capture important dimensions of social sustainability.

Other aspects of social welfare such as exclusion, overall quality-of-life and happiness and other less-tangible and harder-to-quantify measures of human well-being will continue to be a challenge to represent in model-based analytical work, and will require the inclusion of some qualitative descriptors into the analysis. Sometimes this is done within the context of region-specific descriptors of social and political-economic outcomes that have been used in foresight types of studies and assessments such as the GEO-4 studies. The definition of these measures is not always straightforward, however, and must be arrived at by consensus with a wide group of stakeholders who can collectively arrive at a definition that captures the underlying societal priorities and impacts. This type of consultative process requires considerable resources and time, and is best done within a comprehensive foresight-based activity that can provide the needed level of interaction and discussion within a well-structured and organized context. This would be, clearly, beyond the scope of our study, but well within the scope of future foresight-based studies looking at the evolution of the bio-based economy.

5 Wrap up

In this paper, we have considered the various ways in which operational relationships can be constructed across the various modelling tools that are represented within our research consortium. The models that are represented in our study fall into several broad categories – one of which is whether or not they are market equilibrium-driven or not. The global or regional aspect of these models was another consideration, as was the degree to which they focus on multiple sectors, or just a sole sector – such as forestry. The principal 'entry points' for linking these models is either through the prices they simulate – if they are based upon economic market-equilibrium principles – or through the quantities of production, conversion, consumption or exchange that they solve for. Some important aspects of the bioeconomy, such as land and energy, can be linked either through the prices or the quantities that are simulated in these models, whereas other aspects like water availability might be challenging to price directly, although the quantities can be more easily observed and measured.

The linkages between global and regional models is somewhat more straightforward, given that the global models can 'impose' the prices or quantities that are treated as exogenous or belonging to the 'rest-of-the-world' in the regional models – and thereby provide a direct linkage through endogenizing the changes of these factors. The linkage of one global model to another, on the other hand, is more challenging because it involves the harmonization of some key assumptions that might be treated exogenously in both models (such as population growth, global oil prices, climate conditions, assumptions of productivity growth) – and the careful 'tuning' of behavioural parameters (i.e. elasticities) and other model components that would allow them to produce parallel results. This type of 'soft linkage' is more time-consuming, as it involves a more iterative and interactive process between research groups, but is the most realistic approach, in many cases. As is mentioned in the work of Wicke et al (2014), a careful consideration of the type of model collaboration is warranted when trying to determine if mere alignment is required or whether a full-blown effort at integration and linkage must be done.

One of the key gaps that we identify is the extent to which aspects of environmental *quality* can be captured within our proposed framework. Although all of the models represent the quantities of goods and some environmental factors – such as land and water – they uniformly neglect the quality aspects of those natural resources, as would be captured by a degradation of soil or water quality. Even if the initial conditions for these quality aspects could be captured – such as through the initialization of productivities in various agro-ecological zones – it is very difficult to operationalize the feedbacks that future production or consumption behaviour would have on the degradation of quality of land (for example), over time. This is a particularly challenging aspect that only an elaborate modelling exercise, such as that undertaken by the UNEP GEO-4 assessment can hope to achieve. While the resources for carrying out such an exercise are not available to us, at this point, it should remain a point of further discussion and research as to how some critical elements from a GEO-type framework could be brought to bear on the study of the knowledge-based bioeconomy.

6 References

AGMEMOD Consortium 2010. The AGMEMOD Tool Version 4.0 – stylized model equations. Download: http://www.agmemod.eu/index.php/information/the-models.

van Asselen S, Verburg PH. 2013. Land cover change or land use intensification: simulating land system change with a global-scale land change model. Global Change Biology 19: 3648-3667.

van Asselen S, Verburg PH. 2012. A Land System representation for global assessments and land-use modeling. Global Change Biology 18: 3125-3148.

Bouet A, D Laborde. 2010. Assessing the potential cost of a failed Doha Round. *World Trade Review*, 9: 319-351. doi:10.1017/S1474745609990267.

Bouet A, D Laborde. 2012. Food crisis and export taxation: The cost of non-cooperative trade policies. *Review of World Economics*. Springer, 148(1): 209-233.
CAPRI 2012. CAPRI Website. http://www.capri-model.org/dokuwiki/doku.php?.

Chatreuil F, K F Hanrahan, M van Leeuwen (eds). 2012. The Future of EU Agricultural Markets by AGMEMOD. Springer Science.

Christensen, V, CJ Walters. 2004a. Ecopath with Ecosim: methods, capabilities and limitations. *Ecological Modeling*, 172: 109-139.

Christensen, V, CJ Walters. 2004b. Trade-offs in ecosystem-scale optimization of fisheries management policies. *Bulletin of Marine Science*, 74: 549-562.

Daioglou V, APC Faaij, D Saygin, MK Patel, B Wicke, DP van Vuuren. 2014. Energy demand and emissions of the non-energy sector. *Energy Environ. Sci.* 7:482-498. doi: 10.1039/C3EE42667J

Eitelberg DA, van Vliet J, Verburg PH. 2014. A review of global potentially available cropland estimates and their consequences for model-based assessments. Global Change Biology: doi: 10.1111/gcb.12733.

Havlik P, H Valin, A Mosnier, M Obersteiner, JS Baker, M Herrero, MC Rufino, E Schmid. 2013. Crop Productivity and the Global Livestock Sector: Implications for Land Use Change and Greenhouse Gas Emissions. *American Journal of Agricultural Economics*. 95: 442-448.

Havlik P, UA Schneider, E Schmid, H Bottcher, S Fritz, R Skalsky, K Aoki, S De Cara, G Kindermann, F Kraxner, S Leduc, I McCallum, A Mosnier, T Sauer, M Obersteiner. 2011. Global land-use implications of first and second generation biofuel targets. *Energy Policy*, 39(10): 5690-5702.

Hoefnafels R, M Banse, V Dornburg, A Faaij. 2013. Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level – A combined approach for the Netherlands. *Energy Policy*, 59: 727-744. http://dx.doi.org/10.1016/j.enpol.2013.04.026.

Hurmekoski, E. & Hetemäki, L. 2013. Studying the Future of the Forest Sector: Review and Implications for Long-Term Outlook Studies. *Forest Policy and Economics,* 34 (2013): 17–29.

Kallio, A.M.I., Moiseyev, A., Solberg, B., 2004. The global forest sector model EFI-GTM – the model structure. Technical report 15. European Forest Institute, Joensuu, Finland.

Kallio, A.M.I., Moiseyev, A., Solberg, B., 2006. Economic impacts of increased forest conservation in Europe: a forest sector analysis. Environmental Science and Policy 491, 9–18.

Kangas, H-L., Lintunen, J., Pohjola, J., Hetemäki, L. & Uusivuori, J. 2011. Investments into Forest Biorefineries Under Different Price and Policy Structures. *Energy Economics,* 33(2011): 1165–1176.

Laborde D, S Tokgoz, L Shutes, H Valin. 2013. Assessment Framework and Operational Definitions for Long-Term Scenarios. FOODSECURE working paper no 14. LEI Wageningen UR, The Hague.

Laborde, D. 2011. Assessing the land use change consequences of European biofuel policies. European Commission. Report for the EC DG Trade. Atlass Consortium. http://www.ifpri.org/sites/default/files/publications/biofuelsreportec2011.pdf

Laborde D, H Valin. 2012. Modeling Land-Use Changes In A Global CGE: Assessing the EU Biofuel Mandates With The Mirage-Biof Model. *Climate Change Economics*, 3(03): 1250017.

Lotze-Campen, H., Popp, A., Verburg, P., Lindner, M., Verkerk, H., Kakkonen, E., Schrammeijer, E., Schulp, N., van der Zanden, E., van Meijl, H., Tabeau, A., Helming, J., Kuemmerle, T., Lavalle, C., Batista e Silva, F., Eitelberg, D. 2013. Description of the translation of sector specific land cover and land management information. VOLANTE Deliverable D7.3. Download: www.volante-project.eu.

Millennium Ecosystem Assessment (MEA). 2005. Ecosystems and human well-being: Scenarios. Findings of the scenarios working group. Island Press: Washington D.C.

Moiseyev, A., Solberg, B., Kallio, A.M.I., 2010. Modelling the impacts of policy measures to prevent import of illegal wood and wood products. Forest Policy and Economics 12(2010): 24–30.

Moiseyev, A., Solberg, B., Kallio, A.M.I., Lindner, M. 2011. An economic analysis of the potential contribution of forest biomass to the EU RES target and its implications for the EU forest industries. Journal of Forest Economics 17: 197-213.

Moiseyev, A., Solberg, B., Kallio, A.M.I., 2013. Wood biomass use for energy in Europe under different assumptions of coal, gas and CO2 emission prices and market conditions. Journal of Forest Economics 19, 432–449.

Msangi S, M Kobayashi, M Batka, S Vannuccini, MM Dey, JL Anderson. 2013. Fish to 2030: Prospects for Fisheries and Aquaculture. World Bank Report Number 83177-GLB. The World Bank, Washington, DC.

Rosegrant, M.W., X. Cai, and S. Cline. 2002. *World water and food to 2025: Dealing with scarcity*. Washington, DC: International Food Policy Research Institute.

Schelhaas, M.J., Eggers, J., Lindner, M., Nabuurs, G.J., Päivinen, R., Schuck, A., Verkerk, P.J., Werf, D.C. v.d., Zudin, S., 2007. Model documentation for the European Forest Information Scenario model (EFISCEN 3.1.3). Alterra Report 1559 and EFI Technical Report 26. Alterra and European Forest Institute, Wageningen and Joensuu, p.118.

Schneider, UA, P Havlik, E Schmid, H Valin, A Mosnier, M Obersteiner, H Bottcher, R Skalsky, J Balkovic, T Sauer, S Fritz. 2011. Impacts of population growth, economic development, and technical change on global food production and consumption. *Agricultural Systems*, 104 (2): 204-215.

Solberg, B., Moiseyev, A., Kallio, A.M.I., 2003. Economic impacts of accelerating forest growth in Europe. Forest Policy and Economics 5, 157–171.

Solberg, B., Moiseyev, A., Kallio, A.M.I., Toppinen, A. 2010. Forest sector market impacts of changed roundwood export tariffs and investment climate in Russia. Forest Policy and Economics 12(2010): 17–23.

Tokgoz, S., W. Zhang, S. Msangi, and P. Bhandary. 2012. Biofuels and the Future of Food: Competition and Complementarities. *Agriculture*, 2: 414-435.

UNEP (United Nations Environment Programme). 2007. Global Environmental Outlook (GEO4): Environment for Development. Progress Press.

Verkerk, P.J., Anttila, P., Eggers, J., Lindner, M., Asikainen, A., 2011. The realisable potential supply of woody biomass from forests in the European Union. Forest Ecology and Management 261, 2007-2015.

Verkerk PJ, R. Mavsar, M. Giergiczny, M. Lindner, D. Edwards, M.J. Schelhaas,2014. Assessing impacts of intensified biomass production and biodiversity protection on ecosystem services provided by European forests, Ecosystem Services, 9, 155-165.

Wicke B, F van der Hilst, V Daioglou, M Banse, T Beringer, S Gerssen-Gondelach, S Heijnen, D Karssenberg, D Laborde, M Lippe, H van Meijl, A Nassar, J Powell, AG Prins, SNK Rose, EMW Smeets, E Stehfest, WE Tyner, JA Verstegen, H Valin, DP van Vuuren, S Yeh, APC Faaij. 2014. Model collaboration for the improved assessment of biomass supply, demand and impacts. *GCB Bioenergy*. doi: 10.1111/gcbb.12176.

Woltjer G, M Kuiper, H van Meijl. 2011. The agricultural world in equations: An overview of the main models used at LEI. LEI, the Hague.