Jan de Vries

Exploring bioenergy’s indirect effects – economic modelling approaches

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Colofon

Huenderkolkweg 12
7427 RA Deventer
www.2eco.nl

tel +31 (0)570 511543
fax +31 (0)570 511575
mobiel +31 (0)629 432689
email jandevries@2eco.nl

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Table of contents

1. Introduction: background and objectives

During the last decade, production and use of ‘modern’ biomass based energy[1] started to boost, while – according to policy targets in Europe and elsewhere – still much bigger volumes are to be expected in the years to come. This vigorous growth mainly results from policies which are designed to cope with three global mega problems: rising fossil energy prices, global warming and energy security.
The fast rise of bioenergy, however, appears to be controversial as well. E.g. recent analyses seriously question the supposed benefits of bioenergy for the global carbon balance. Also, many observers blamed the increase of energy-crop cultivation to be a main cause of the 2008 food (price) crisis.
Due to such controversies, the very rationale of bioenergy stimulating policies needs reconsideration. The crucial question here is: will bioenergy – yes, yes if, or no – maintain its status as an attractive option, worthy to support? Moreover, assuming that the answer is a stipulated ‘yes, if...’, such policies need to be redesigned. Than the next question goes: how can it be assured that the benefits of bioenergy are reaped, while unwanted impacts are avoided or at least minimized?

Characteristically, beneficial and adverse impacts of bioenergy are intertwined in complex ways. This complexity stems from a multitude of causal relationships (not to forget the effects of chance and risk; think alone of weather impacts, or the volatility of energy prices), in divergent time- and scale frames. Indirect effects, especially induced changes in land use, play a crucial role for the ultimate balance.
One way to analyse such real world complexities is to simplify them rigorously, while maintaining their key components, connections and mechanisms in sight. In other words, to build a virtual but representative, reliable model, preferably in a manner which enables to simulate the dynamics of – in this case – bioenergy growth and impacts. Of course, the ‘behaviour’ of such virtual models is not identical with world realities. Careful consideration hów reliable the model is, should never be forgotten. But with this proviso kept in mind, model exercises may clarify complex, many-sided developments like bioenergy-growth more than other analytical methods will be able to do.

In recent years, model-based research on the impacts of bioenergy has been intensified worldwide. A number of studies are published or to be published on short term. Often the researchers employ existing, well reputed models, which however had to be adjusted and extended to capture the peculiarities of bioenergy and its impacts. Such extensions and adjustments are seldom tested before, so their reliability deserves special consideration.

The Netherlands Environmental Assessment Agency (PBL – Planbureau voor de Leefomgeving) is actively engaged with both questions mentioned above – the attractiveness of bioenergy as such, seen from a sustainability perspective; and the ways to avoid adverse impacts of bioenergy, while reaping its benefits. This engagement stems from PBL’s advisory role towards Dutch and European policy makers in general; as well as from its participation in specific projects, like the design of certification schemes.

Against this background, the PBL wants to take stock of the progress which has been made recently in model-based research on bioenergy, especially in modelling indirect effects like land use change. This report partly provides in this need. Its objective is:

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[1] As opposed to traditional ways of using bioenergy, like fire wood.

- to give a short overview of different modelling approaches, including their qualities and weaknesses in the context of new developments like bioenergy;
- to evaluate recent applications related to bioenergy production, focusing on their analytical framework rather than their outcomes;
- and to give a provisional, 'ex ante' judgment about their reliability.

This report does nót intend to compare and evaluate the *outcomes* of the models, presented here. This may well be the subject of future work, relevant when several promising studies are completed which these days only exist as prospects.

This report reads as follows. Chapter 2 sets out the main characteristics of different types of models, discussed in this report. As such, it serves the first objective, mentioned above. Chapter 2 also presents the criteria, used to qualitatively assess model applications.
Chapter 3, 4 and 5 proceed with discussing relevant applications of partial equilibrium models, general equilibrium models and (a few) non-economic models respectively; the choice of which was made in consultation with PBL. Chapter 6 outlines the overall picture, including provisional conclusions on the reliability of model-based analyses of bioenergy growth and impacts.

An earlier version of this report was completed in July 2009. In this extended version, several models were added to chapters 3 (IMPACT and GLOBIOM/ASMGHG) and 4 (DART, MIRAGE and GTEM), while chapter 5 as a whole was added. The treatment of models, included in the earlier version, has not been updated however, except for a few corrections and comments we gratefully acknowledge.

2. Modelling approaches, main characteristics and evaluation criteria.

Economic and non-economic approaches

Widely different types of models have been used to analyse bioenergy growth and impacts. A first distinction can be made between economic and non-economic models. In economic models, market mechanisms – the equilibrating interplay between demand and supply – deliver the crucial feedback loops, determining prices and quantities of bioenergy as well as prices and quantities in related markets. Non-economic models on the other hand, primarily lean upon forecasting techniques like linear programming, trend extrapolation, input-output matrices and system-dynamics. In other words, economic models build on behavioural reactions – producers and consumers responding to price signals – which are supposed to be the dominant adaptive mechanism in market economies; non-economic models do not, or at least not in a comprehensive way.

Within the field of economic modelling, a further distinction can be made between micro- and macro-level models. Micro-level models – like cost accounting, resource allocation and technology adoption models – analyse the economics of bioenergy from the perspective of an individual bioenergy producer or consumer. This category of models is largely ignored in this report, because in general they are not suited to provide understanding of the indirect effects of bioenergy. Macro-level models analyse aggregate growth of bioenergy and its impacts, either within certain sector boundaries (so called partial equilibrium (PE-)models), or within the economy as a whole (so called applied or computable general equilibrium (AGE/CGE-)models[2]). PE- and GE-models are the main focus of this report, given their prominent status in the international arena of bioenergy observers, advisors and policymakers.

Besides PE- and GE-models non-economic modelling approaches are of importance. Models of this type are sometimes used in stand-alone fashion; but more often they are applied as a complement to economic models, either as a source of input-data or as a means to further analyse certain outputs (like environmental consequences). Such combinations appear useful to overcome an inherent weakness of purely economic modelling of bioenergy growth and impacts, namely the difficulty to capture interactions, feedback mechanisms etc. which do *not* proceed through markets (like external, environmental effects; or informal economies' production and consumption).

So, the main emphasis of this report is on applications of two types of models: sector-confined PE-models and economy-wide GE-models (chapters 3 and 4, respectively). Within both categories some attention is given to studies in which economic and non-economic modelling of bioenergy growth and impacts has been combined. Moreover, in chapter 5 three models are shortly discussed in which non-economic modelling is the dominant approach. This report is also confined to model applications with a global or at least regional (in the sense of world regions) coverage.

Main characteristics of economic models

Partial equilibrium models treat bioenergy production as part of the agricultural sector (which may include forestry). Usually this agricultural sector is modelled in a rather detailed manner, e.g. including some tens of primary agricultural commodities with their own supply and demand functions, differentiated for countries, world-regions or so called agro-economical zones. Potential effects from the agricultural sector on the rest of the economy are ignored; effects in the opposite direction are typically taken up by adjusting exogenous variables. Such models are frequently used

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[2] Within our context, applied and computable general equilibrium models can be considered identical. So, we will simply refer to them as GE-models.

to analyse past and future changes in agricultural prices and quantities and related parameters like farmers income and food prices; including the impacts of governmental policies like agricultural subsidies, trade barriers or regulated food prices.

The strengths of agricultural PE-models lie – generally speaking – in their relatively high level of sectoral, regional and institutional detail, which make them potentially attractive for analyzing bioenergy growth and impacts. However, these strengths come at some cost. This cost is partly unavoidable, because due to the neglect or strongly simplified treatment of interactions with the rest of the economy in PE-models; partly accidental, so far it is due to specific design features. Belonging to the first category is a well-known tendency of PE-models, namely to overestimate the magnitude and impacts of agricultural market disturbances, as a result of not considering moderating influences from the rest of the economy. Such adjustment processes take time, however, so another way of referring to this weakness is to say that results from PE-model exercises are primarily short en medium term related (one to several years).
Likewise inevitable is the incomplete treatment of bioenergy production as an agro-*industrial* sector, competing with traditional energy producers. E.g. PE-models usually focus on primary agricultural commodities (in our case: energy crops). So doing, they may overlook relevant developments in the industrial processing part of bioenergy production chains. Or, other example, their treatment of energy prices as exogenous variable fails to take into account the fact that growing energy crops gives birth to a two-sided relationship between agricultural production and energy prices (energy becoming an agricultural input ánd output factor; see Schmidhuber, 2006).

Other weaknesses are more or less accidental, because connected with design features of specific PE-models. Van Tongeren et al (2001) describe the prototypical agricultural PE-model, applied during the nineties, as

- being (multi-)regional in scope (i.e. world regions like EU, North America, Asia etc), with global coverage by including some 'rest of the world' region;
- delivering comparative static analyses, thus ignoring the time path as well as stock related (e.g. capital stock, stocks of land) adjustment processes towards a new (partial) equilibrium;
- not including factor markets, thus ignoring factor movements between sectors (inputs like labour and land are treated as exogenous variables instead);
- not including product differentiation according to country of origin or product qualities, implying that only intersectoral trade occurs, with trade patterns depending on world market prices only (except when trade barriers are in place).

Van Tongeren et al note that most agricultural PE-models are 'pretty close' to this standard version (compare table 2.1; this snapshot refers to the situation early 1999). Nevertheless some models deviate, either by their original design, or as a result of successive improvements. Two extras seem most important in the context of bioenergy. Firstly, the inclusion of land allocation as in OECD's AGLINK model and FAO's World Model. And secondly, the (recursive) dynamic features of several models, including again AGLINK and the World Model; meaning that such models allow to plot a sequence of temporary, successive equilibriums, in correspondence with adjustment of exogenous variables and stock parameters.

General equilibrium models, on the other hand, treat bioenergy growth and impacts within the context of national (respectively regional) economies as a whole. Such a comprehensive approach implies that supply and demand functions need to be specified for all product markets (i.e. final and intermediate products from and to all sectors, including international trade and consumers); as well as for factor markets (i.e. capital, labour and land, allowing for factor movements between sectors) and financial markets (including investment- and savings-rates, trade balance, exchange rates etc.). Moreover, all price and quantity relations within a GE-model are interrelated by substitution elasticities, acting within macro-level constraints. This model property enables to prospect adjustment processes throughout the economy after disturbances, resulting in trends towards recovery of equilibrium on all markets.

Tabel 2.1 Characteristics of agricultural PE-models *(Source: Van Tongeren et al, 2001; adjusted)*

	Description	Modelling of trade	Policy representation	Global coverage	Number of regions (R) or countries (C)	Number of sectors/ products
Standard model	Static partial equilibrium, global coverage, no factor markets included	Homogenous good + pooled markets	Price wedges			
AGLINK	Recursive dynamic model includes land allocation	Standard	Quantity restrictions modelled explicitly	Yes	11 C + 2 R	19
ESIM	Standard model, land market included, special emphasis on Eastern Europe	Standard	Quantity restrictions modelled explicitly	Yes	7 C + 2 R	27
FAO World Model	Recursive dynamic model includes land allocation	Standard	Price wedges	Yes	147 C + 1 R	13
FAPRI	Econometric recursive dynamic model, special emphasis on the USA	Standard	Price wedges	Yes	29 C+R	24
GAPsi	Recursive dynamic model	Standard	Quantity restrictions modelled explicitly	Yes	13 C + 4 R	13
MISS	Standard model	Standard	Quantity restrictions modelled explicitly	No	1C + 3 R	10
SWOPSIM	Standard model	Standard: base model; Armington: one application	Price wedges	Yes	36 R	22
WATSIM	Standard model	Standard	Quantity restrictions modelled explicitly	Yes	4 C + 10 R	29

GE-models have an established reputation in analysing resource allocation issues, e.g. reallocation of production factors among sectors, including the indirect economic (so called ‘second round’) effects of reallocation. In fact, when significant second round effects are to be expected, then GE-models provide the only instrument to analyse these in a economically coherent way.

The attractiveness of GE-models is connected with this ability to reveal interrelated shifts and transformations throughout the economy, when structural changes take place like a substantial switch within the energy supply system towards bioenergy. But evidently, GE-models have limitations and weaknesses too. At least three limitations seem important in our context. Firstly, the inherent complexity of GE-models forces modellers to limit sector and regional disaggregation and the level of institutional detail. E.g. the number of primary agricultural products seldom exceeds ten. As a result, the design of GE-models may be too big-boned to enable recognition of the impacts from a single production chain like bioenergy. Secondly, modellers are tempted – for the same reason: reducing complexity – to introduce simplifying but unrealistic assumptions like perfect competition, unconstrained factor mobility or unembarrassed free trade. Such GE-models, however, may overrate the extend and speed of equilibrating adjustment processes. And thirdly, the difficulty to internalize non-economic impacts (like external effects, as mentioned before) within GE-models should be remembered.

Table 2.2 Characteristics of agriculture-oriented GE-models *(Source: Van Tongeren et al, 2001; adjusted)*

	Description	Modelling of trade	Policy representation	Global coverage	Number of countries (C) or regions (R)	Number of sectors/ products
Standard model	Applied general equilibrium, multi-sector, comperative static, constant returns to scale in production, perfect competition on all markets, global coverage	Armington bilateral flows	Ad valorem price wedges			
G-cubed	Intertemporal applied GE and macroeconomic model	Standard	Standard and tradable emission permits	Yes	4 C + 4 R	12
GTAP	Standard (default version); recursive dynamic and monopolistic competition versions available	Standard, monopolistic competition version available	Standard in default version, volume & value restrictions available	Yes	27 C + 12 R + RoW (Rest of World)	50
GREEN	Recursive dynamic	Standard, except crude oil (homogeneous)	Standard, quota, tradable emission permits	Yes	5 C + 7 R	9
INFORUM	Linked system of dynamic national macro-econometric models with inter-industry input-output linkages	Price and income sensitive econometrically estimated import/ export equations	Standard, macro-economic policy instruments, taxes and transfers	No	13 C	Varies by country: 33 – 100
MEGABARE and GTEM	Recursive dynamic, endogenous population growth, technology bundles in electricity and iron & steel	Standard	Standard and tradable emission permits	Yes	27 C + 12 R + RoW	50
Michigan BDS	Scale economics and monopolistic competition in manufacturing industries	Monopolistic competition	Standard	Yes	34 C + RoW	29
RUNS	Recursive dynamic	Manufacture: standard; Agriculture: homogeneous goods and pooled markets	Standard	Yes	13 C + 9 R	20
The WTO housemodel	Standard and imperfect competition versions	Standard and firm level product differentiation	Standard, import quota	Yes	5 C + 7 R + RoW	19

According to Van Tongeren et al (2001) characteristic features of 'first generation' GE-models are

- multi-sector, economy-wide coverage, using sectoral production functions with substitutability of primary factors but assuming fixed intermediate input proportions and constant returns to scale;
- including factor markets with complete competition and full (labour/capital) or imperfect (land) domestic mobility across sectors;
- including product differentiation according to country of origin, allowing for bilateral, inter- ánd intra-sectoral) trade flows;
- delivering comparative static analyses, ignoring the time path towards a new (general) economic equilibrium.

However, already in the nineties 'second' and 'third' generation GE-models came up, which were enriched with several 'real world'-features, like positive scale effects, monopolistic (incomplete) competition, product differentiation other than according to country of origin, and recursive dynamic behaviour. Van Tongeren et al's overview of GE-models with agricultural focus and global coverage, snapshotted early 1999, illustrates this development, by showing a diversity of model features (see table 2.2). Some new features already dominated the scene at that time, especially the recursive dynamic approach.

Evaluation criteria

Besides on their inherent strengths and weaknesses as set out above, the reliability of PE- and GE-models also depends on specifics. Of prime importance are the adequacy of the *equations,* defining relationships between components of the model, and the adequacy of *datasets*[3]*,* used to quantitatively calibrate the model (including values of elasticities and exogenic parameters).
So, the way equations are specified and the quality of datasets are two important criteria we will look at when discussing model-based analyses. As a third criterion we will pay some attention to the prospective quality of the models, including such aspects as time horizons, calibration and validation, and sensitiveness analyses.
As much as possible we will focus our review of each model on its treatment of bioenergy, its treatment of land use impacts, and its treatment of environmental impacts, especially on the greenhouse gas balance.

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[3] The concept 'dataset' is used in a comprehensive way, e.g. including the use of literature-based elasticity values.

3. Bioenergy analyses using partial equilibrium models

3.1 OECD/FAO's Aglink/Cosimo model

3.1.1 General features

The Aglink/Cosimo modelling system, applied by OECD and FAO, is one of the most renown agricultural sector models with global coverage. Originally the Aglink model was developed by the OECD in the early '90-ties, with emphasis on the developed world, respectively temperate zone agricultural products. According to Van Tongeren's evaluation (see chapter 2), already in 1999 Aglink ranked as a partial equilibrium model with advanced features, such as its (recursive) dynamic character and a rather detailed agricultural sector and policy representation. Essentially it consists of country specific supply and demand equations, including domestic policy variables; market clearing involves international (net) trade, balanced by world equilibrium prices (taking into account actual and prospected import tariffs).
The model lacks however production functions for agricultural commodities, in which land would appear next to other production factors. Instead there are supply equations, as already mentioned, based on gross returns (e.g. returns per hectare) and a production cost-index (i.e. a correction factor to account for inflation and exchange rate changes). The absence of production functions implies that productivity improvements and factor shifts are not endogenously prospected by the model, but are to be introduced exogenously.

Since 2004 the geographical coverage of Aglink has been improved through collaboration with FAO's Cosimo-model, which shows a comparable design and represents the agricultural sectors and policies of many developing countries. Key application of the combined Aglink/Cosimo model is the Agricultural Outlook, published annually by OECD/FAO and presenting projections and market analyses over a ten year horizon.

Next to the Outlook, the Aglink/Cosimo model is used regularly to analyse the impacts of alternative policy scenarios against the benchmark of baseline projections. In view of such analyses, modifications of the model (regarding its database and/or the equations and parameters used) are introduced, and adjacent models are applied in combination with or integrated within the main model; e.g. OECD's Sugar Market model.
So, in 2006 the OECD presented a first report on the impacts of increased bioenergy (biofuel) production on agricultural markets (Von Lampe, 2006). To foster this analysis the Aglink/Cosimo model had been modified in two ways. Firstly, the country modules of four major bioenergy producers[4] – USA, Europe, Canada and Poland – were extended with sub-modules representing, in a rather simplified way, (first generation) bioethanol and biodiesel production from agricultural feedstocks. And secondly, an energy cost parameter was introduced in the supply equations of all crops and lifestocks, reflecting the increased importance of rising crude oil prices for agricultural production; not just for bioenergy.

In 2008 a second report saw daylight, assessing the economic rationale of biofuel support policies, with again Von Lampe as main author (Von Lampe, 2008). In the same year, bioenergy got prominence as a separate chapter in the Agricultural Outlook 2008-2017 (OECD/FAO, 2008). In this context the Aglink/Cosimo model was further improved, by fully integrating the Sugar Market

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[4] Brazil's sugarcane/ethanol production had been modelled earlier within the Sugar Market model. This representation was not extended in Von Lampe (2006).

model and by replacing Von Lampe's (2006) biofuel module by a more comprehensive version, applied to the main biofuel producers (USA, Europe, Brazil, Canada). In addition biofuel production in 13 developing countries was represented too, be it in a less sophisticated way. And finally, a new model – SAPIM: 'Stylized Agri-environmental Policy Impact Model' – was applied in combination with Aglink/Cosimo, to analyse micro-economic impacts (i.e. decision making by farmers) and environmental effects of biofuel related policies.

We consider Von Lampe (2008) and the Agricultural Outlook 2008-2017 to reflect Aglink/Cosimo's 'state of the art' applications regarding bioenergy. Therefore in the next paragraphs, while shortly referring to Von Lampe's 2006 report, we will focus on these publications.

3.1.2 Treatment of bioenergy

Von Lampe (2006) treats biofuel production as an additional demand for certain agricultural commodities: vegetable oils as feedstock for biodiesel, and wheat, maize (coarse grains), sugar cane and sugar beet in the case of bioethanol. At the same time biofuel production provides by-products, i.e. additional feed commodities to be used in lifestock production. Essentially, the biofuel model in his report contains of three elements:

- Von Lampe first of all models the development of agro-industrial production capacity, in other words the increase of ethanol and biodiesel industries. In his equation, this capacity depends on three variables: (1) a trend annual growth rate, (2) the biofuel/conventional fuel price-ratio (as the average over three preceding years), and (3) an exogenously determined capacity adjustment factor. Factor 3 represents a first option to account for politically determined growth.
- The biofuel cost-price (numerator in the price-ratio mentioned above: factor 2) in its turn depends on domestic feedstock prices, plus energy- and non-energy costs, plus the net incidence of taxation and subsidies, and minus the value of by-products. In this equation, the tax/subsidy variable represents a second option for political intervention.
- Von Lampe's assumption is that (apart from short term deviations) biofuel consumption follows capacity development at the domestic/regional level: the possibility of biofuel trade is not envisaged in his analysis. However, trade in feedstocks and biofuel by-products, being agricultural commodities normally distinguished in Aglink, is possible as usual.

The result is that economic effects of biofuel production find their way through agricultural markets. The additional demand for feedstocks and the additional supply of by-products influence prices and quantities of these commodities, both at the domestic/regional level and at the global level (through shifting trade patterns).

This way of modelling enables Von Lampe to analyse different scenario's, by manipulating variable 3 in his capacity equation (politically determined capacity growth), and/or the tax/subsidy variable in his biofuel cost equation, and/or the crude oil price. This last (exogenous) parameter affects the model along two routes: it influences the price of conventional transport fuels (denominator of the biofuel/conventional fuel price-ratio, see above), and it represents a cost variable within agricultural supply equations.

In several respects, Von Lampe (2008) presents a more sophisticated treatment of bioenergy. Firstly, the equations for biofuel production capacity, cost-price and demand were reformulated. And secondly new features were introduced, notably biofuel trade and second generation biofuel production. Comparing with Von Lampe (2006), we list the most remarkable improvements:

- In the capacity equation, the variables 1 and 3 (see above), representing a trend annual growth rate and a exogenous adjustment factor, are maintained. But the second variable, the price ratio between biofuel and conventional fuel, is replaced by a variable representing a producer's expected profit relative to his investment. This profit expectation is indicated by a proxy, namely the ratio between his net proceeds from selling biofuels (including direct, output related subsidies) and his capital costs; measured over the current and four preceding years.

- In the biofuel cost-price equation little has changed, except a distinction between capital costs and other costs (instead of distinguishing energy and non-energy costs), and the introduction of a distinct variable for one by-product of biofuel (ethanol) production, namely DDG (distillers dried grains).[5]
- The assumption that demand follows capacity growth is replaced by a rather detailed modelling of biofuel demand. In the case of bioethanol, its use as additive, low-level blend, or high-level blend/neat fuel are distinguished; the last component presupposes the availability of flex fuel vehicles. In case of biodiesel only low-level blends are relevant. Each demand component has its own demand equation, mainly depending on the price ratio (retail prices, including tax and/or subsidy) between the biofuel blend or additive and conventional fuel. Values of this price ratio are set, above (below) which zero (full) preference for biofuel is assumed; within the intermediate interval a substitution process is expected, in which the price ratio as well as non-price considerations (like consumer preferences for supposedly green fuels) play a role.
  Also, in the case of low-level blends of bioethanol and biodiesel, biofuel mandates may apply. If so, than the price ratio variable in the demand equation is overruled by such obligatory minimum levels.
- Newly introduced are equations describing biofuel trade. These equations imply that differences between biofuel volumes produced and consumed domestically, will be levelled out by import/export. They also imply that one world market price will emerge for each type of biofuels, ensuring that global net exports equal global net imports. Domestic (wholesale) prices may only diverge from this world market price in case of importing countries/regions, and only to the extent of their import tariffs (if such tariffs are imposed).
- Also newly introduced into the biofuel module is the predicted, but still infant production of second generation biofuels – notably bioethanol from cellulose and biodiesel produced by Fisher-Tropsch synthesis – however in an ad hoc way, with exogenously fixed production volumes and no trade assumed. Three categories of second generation biofuels are distinguished, depending on their relevance for agricultural markets, that is whether produced from dedicated crops, from agricultural residues or from non-agricultural sources.
  Obviously, the third category does not influence agricultural markets directly; it may have indirect effects, as this additional supply enters biofuel markets and hence affects biofuel prices. This category is only for this reason included within the model.
  The second category, representing a co-product which may generate additional revenues if used for biofuel production, will increase incentives to produce the main product. This effect is accounted for by inserting an additional variable in the crop production equations (returns per hectare) of cereals. Considerations as to whether residues are applied for biofuel production or for current applications (like fertiliser, soil quality maintenance) are captured by a cost equation, including variables representing the opportunity cost of ending such uses.
  The first category – production of second generation biofuels from dedicated crops – appears to be the most promising, but also most uncertain and disputed one. Here a production cost equation is introduced, including the agricultural as well as the industrial phase of this production chain. Interestingly, agricultural costs (biomass production) include capital and management costs, labour costs and land rents.[6] It is stated that in this equation land rents are 'obviously crucial' for the interaction between second-generation biofuel production and

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[5] The DDG variable relates to the comprehensive modelling of DDG, with supply and demand equations, as a part of the biofuel module. This special treatment of DDG is motivated by the absence (contrary to other by-products) of a DDG-market in Aglink/Cosimo's standard version.

[6] Note that this specification differs from the normal agricultural supply functions in Aglink/Cosimo, which simply assess gross revenues, corrected by a cost index.

agricultural markets, and therefore should be endogenised. In Von Lampe (2008) however, land rents are fixed exogenously, as are the other variables in this cost equation. The modelling of dedicated crops is completed by a couple of equations, representing land use impacts: total acreage, calculated from exogenously assumed yields; deduction of a share, representing land not suitable for food production; and finally reduction of certain food crop areas (wheat, coarse grains, oilseeds), corresponding with the remaining acreage. In other words: dedicated crop production is supposed to take place within existing agricultural areas.

3.1.3 Data reliability

The interplay between different factors in model-equations depends on the functional form of each equation, as well as on the value of coefficients (elasticity's, time dependant indices, scale parameters etc) of such factors (respectively the factor itself). Such model specifications are usually based on a mix of theoretical considerations, empirical (historical) evidence and plausibility (i.e. expert opinion). In case of models with a long standing record, experience may also play a role (based on ex post evaluation of model applications).

So, Von Lampe's (2006 and 2008) analyses partly build on evidence, gathered during many years practising the Aglink/Cosimo model. E.g. coefficients representing agricultural productivity (yearly yield improvements) reflect long term trends, specified for different crops and lifestock products in different regions.
The available evidence behind the newly introduced features of the Aglink/Cosimo model is much weaker, however, as Von Lampe explicitly recognizes. E.g. the coefficients connected with the energy-price parameter, introduced in agricultural supply functions, are based on the shares of agricultural cost elements currently found in two countries – Argentina and USA; these shares were simply assumed to apply for all non-OECD respectively OECD countries. Coefficients regarding biofuel production from a specific feedstock were generally based on experience in one country, and than applied to all.

Lack of data forced Von Lampe (2006) also to insert other simplifying assumptions. E.g. the autonomous growth trend of biofuel production capacity (variable 1 in the capacity equation; see above) was set at 5%/year for ethanol and biodiesel in all regions, except 3%/year for ethanol-USA. Other example: the shape and level of political stimuli was modelled in a rather stylized way, by assuming that biofuels in all regions[7] are exempted from fuel-taxes and no subsidies are given; in other words, the tax/subsidy variable in the biofuel cost equation (see above) was set at zero. In Lampe (2008) the limited data availability, obviously, also regards the assumptions on second generation biofuels.

3.1.4 Treatment of land use impacts

Von Lampe's (2006) report focuses on the impact of biofuel production on agricultural markets, in terms of world market prices and volumes (produced quantities) of agricultural commodities, including shifts in the allocation of production and hence in trade patterns. Clearly, changes in production volumes as well as in allocation imply land use changes, at least within agricultural (crop) areas and possibly by increasing crop area, e.g. by utilizing fallow lands and/or conversion of non-agricultural land.

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[7] Except Brazil, for which detailed information on the biofuel tax regime was available.

However, evaluating such land use impacts of biofuel production is absent in Von Lampe's report, or – more precisely – it does not result from his Aglink/Cosimo model application[8]. This has primarily to do with limitations of this model in which neither a land market is represented, nor agricultural production functions (which would include land as a production factor) are specified.

Von Lampe (2008) firstly points at limitations of the Aglink/Cosimo model, which does not account for different types of land with varying productivity, varying carbon stocks etc. The model only enables to assess aggregate area changes for the main crops. So, in this report some aggregate estimates of land use impacts from first generation biofuels are derived, relative to a baseline tendency of increasing crop areas world wide, but shrinking crop areas in some regions (especially in Europe). It appears that both direct effects of biofuel production (land, used for biofuel feedstock cultivation), and indirect effects (high crop prices, which improve farm profitability) contribute to land use impacts.

Possible land use effects of second generation biofuels are estimated by introducing additional assumptions, about the share of feedstock cultivation on agricultural respectively non-agricultural land. In other words, the estimations regarding second generation biofuels are primarily exogenously determined, in stead of an endogenously derived outcome of the model.

As noted above, Von Lampe (2008) also presents a supplementary model – SAPIM: 'Stylized Agri-environmental Policy Impact Model' – which intends to overcome certain Aglink/Cosimo limitations. SAPIM models:

(a) decision making by individual farmers, representing micro-economic optimization under heterogeneous conditions (including specified policy incentives); this includes choices on input use intensity (the 'intensive margin'), on land use allocation (the 'extensive margin') and on farm continuation (the 'entry-exit margin');
(b) site specific biophysical variables, which influence agricultural productivity as well as environmental sensitivity across different types of land. Environmental outcomes are reported in physical terms, but may also be valued in monetary terms and as such integrated into the micro-economic optimization according to (a).

SAPIM outcomes at farm-level can then be cast up and summarized in terms of aggregate private or social benefits. SAPIM is applied in combination with Aglink/Cosimo, from which it imports agricultural prices. It is not clear however whether SAPIM results are fed back into Aglink/Cosimo, in other words whether both models are bilaterally coupled, e.g. through an iteration procedure. The geographical coverage of SAPIM's database is as yet unknown; Von Lampe (2008) only reports on a illustrative, local SAPIM application, based on empirical data from south-western Finland.

3.1.5 Treatment of GHG-balance and biodiversity impacts

Von Lampe (2006) explicitly does not cover environmental implications of biofuel production. Von Lampe (2008) points at the supplementary SAPIM model, which assesses multiple environmental effects related to:

- surface water quality: nitrogen, phosphorus and herbicide run off;
- biodiversity: quality of wildlife habitats; and
- climate: GHG emissions from agricultural inputs (like fertilizer and herbicides), practices (like tillage, harvesting, grain drying) and related transport.

Application of the SAPIM model seems at preliminary stage; see per. 3.1.4.

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[8] The report does present estimated land requirements for an optional 10% biofuel share in domestic transport fuel consumption (using simplifying assumptions like zero productivity increases in agriculture and industry, unchanged feedstock allocation, absence of feedstock and biofuel trade), but the calculation of these estimates is completely detached from the Aglink/Cosimo model application.

3.2 EU's European Simulation Model (ESIM)

3.2.1 General features

The ESIM model was developed in the mid '90-ties on request of the European Commission, by USDA-Economic Research Service and the University of Göttingen. At its start it was designed as a static PE-model with special emphasis on EU-member states and Eastern European accession candidates. Nine countries/regions and approximately 25 commodities were distinguished. Later on certain dynamic features were introduced, like trend parameters (so called 'shifters') to represent e.g. increasing productivity and income growth. But other features, usually applied in dynamic models are absent, like lagged price responses. So, by some observers ESIM is still considered a static model (e.g. Nowicki et al, 2007), while by others it is presented as a recursive dynamic model (e.g. CEC, 2007).

ESIM's country- and commodity coverage was widened considerably in following years, including some energy crops (Banse et al, 2005). Its European orientation was maintained however, as only US and a rest-of-the-world aggregate are distinguished besides all European countries. Finally, in 2006, a more extended bioenergy module was introduced, including production and use of first generation biofuels (bioethanol, biodiesel), the feedstocks (energy crops) used and by-products (feeds) produced. Including energy crops and products, some 40 primary and processed commodities (including 'pasture' and 'voluntary set aside' as 'other products') are now distinguished.

ESIM also comprises many policy instruments, like tariff rates and quota's, intervention prices, export and product subsidies, direct payments, production quota's etc.

Within ESIM, land allocation proceeds in two steps. Firstly, allocation for each crop is modelled, depending on its price, prices of other crops and a cost index (covering labour, capital, intermediate goods). This equation, in combination with a yield equation, determines supply and reflects the assumed profit maximizing behaviour of farmers. Secondly, the aggregate of all crop areas is scaled up or down, to equalise this aggregate with the total available crop area (adjusted for obligatory set aside), which is exogenously fixed. Note, however, that pasture and voluntary set aside are 'commodities' in ESIM, which implies that the relative share of these areas are endogenously fixed by the model.

Commodity demand depends directly or indirectly – in case of processed commodities – on domestic prices (own price and other prices), income growth and population growth. All equations are in domestic (i.e.: EU-) prices, or related concepts like EU-producer prices. There is however a price transmission equation, which links EU-prices with world prices, while accounting for trade- and price-policies. So, the model solves simultaneously for all crops at global level, including trade from and to a relatively autonomous Europe.

Currently, ESIM is one of EU-DG AGRI's 'in house' models, e.g. applied to produce yearly agricultural outlooks over a 7-years time horizon. It is also used for policy impact analysis, e.g. regarding the 10% biofuel target as was proposed by the European Commission in 2007. For a second application, in combination with the CAPRI model, see par. 3.3.

The ESIM model is hosted by JRC-IPTS, and maintained in cooperation with DG-AGRI and external researchers.

3.2.2 Treatment of bioenergy

Following the (brief) description of Nowicki et al (2007), the biofuel module includes a detailed processing sector, producing first generation bioethanol and biodiesel from cereals and sugar beets, respectively from oilseeds and vegetable oils (like palm oil). The main by-products are modelled too, with their impacts on feed markets, as is net trade in biofuels with US or the Rest-of-the World aggregate.

Biofuel demand is represented, depending on the price ratio with conventional fuels and especially on domestic (country specific) policies like tax allowances and blending mandates.

Additionally, CEC (2007) states that also land use implications of second generation biofuels were assessed by applying the ESIM model, assuming a 30% share of cellulosic ethanol and BTL in 2020, produced from straw and wood chips. The relevant equations are not presented, however. Probably, yield and area parameters are exogenously fixed.

3.2.3 Data reliability

The ESIM model is regularly recalibrated, starting from base-year price and quantity data from Eurostat; with regard to bioenergy additional data from FAPRI (see par. 3.4), F.O. Licht and other sources are used. Elasticities are mainly taken from literature.

3.2.4 Treatment of land use impacts

European feedstock production, used for biofuels, enters the normal area allocation function of ESIM (see above). Some equations are adjusted in order to capture the current exemption from set aside obligations and to exogenously introduce higher price elasticities. This treatment results in a picture, showing how energy crops will seize a certain share of arable land – at the cost of other crops –, and/or actually unused land (set aside) or eventually grassland. Capturing non-agricultural lands is excluded by model design. Land use, connected with imported biofuels (or biofuel feedstocks) are not analysed (as such products are simply imported against a world market price), neither are indirect land use effects from displacement of other crops.

3.2.5 Treatment of GHG-balance and biodiversity impacts

The ESIM model is not capable of analysing impacts on GHG-balance or biodiversity.

3.3 EU's CAPRI Model

3.3.1 General features

The 'Common Agricultural Policy Regional Impact' (CAPRI) model was first built by the Institute for Food and Resources Economics (ILR, according to its German acronym) of Bonn University, at the end of the '90-ties. Since 1999 (first operational version), its development is founded on an open network approach, engaging many users and researchers, with ILR acting as the model clearinghouse.

The CAPRI model conceptually consists of two modules, the results of which are linked by an iteration procedure.
(1) The *supply module* includes 250 independent, regional programming models, together covering EU-27 plus Norway, Western Balkans and Turkey. Originally about 40 crop and livestock production processes were captured in high detail, including e.g. regional land, feed and plant nutrient constraints, different crop cultivation practices (high and low input), processing activities, EU-CAP premiums and other policy measures, etc. (Britz, 2005). Later other products are added, including biofuels, their main feedstocks and by-products (www.capri-model.org). Data are derived from EU-agricultural statistics. These regional models are solved simultaneously, maximizing regional agricultural income at given prices; results are then aggregated to national level.
(2) The *market module* is designed as a comparative static PE model with bilateral trade, distinguishing some 50 primary and processed agricultural products and 60 regions/countries world wide (including all EU Member States). Data (except for EU) and projections are FAO-based. Parameters/elasticities are mainly taken from literature. This module allows for market analysis at global, EU and national level, including impacts from trade and trade policies (like tariffs). It is solved by equilibrating prices and quantities on all agricultural markets.
The iteration procedure starts with importing the results from the supply module, representing the supply response of EU-agriculture on a given set of prices, into the market module; solving this module delivers new prices, which are then used in the next iteration of the supply module; and so on, till results of both modules coincide.

Next to solving its two constituting modules and their iteration, the Capri model also enables post-model calculations of environmental impacts, notably fertilizer related emissions (like nitrogen leaching, ammonium, phosphate), non-CO_2 greenhouse gases (methane, nitrous oxide) and several biodiversity indicators (e.g. Shannon index, Simpson's diversity index); spatially downscaled to 1x1 km grid level.

The CAPRI model has been used frequently to evaluate (ex ante) impacts from EU agricultural policies. It also functions as a core component in several combined model applications, like SCENAR 2020 (Nowicki et al, 2007), SENSOR (Jansson et al, 2008a) and SEAMLESS (Britz et al. 2009; Van Ittersum et al. 2008). All of these are integrated EU-funded research projects, in which one or more economy-wide GE-models[9] are combined with sector specific models (like PE-models for agriculture and/or forestry); sometimes also a spatial land use model is included. These projects intend to yield 'the best of both worlds': great scope ánd considerable detail.

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[9] In SCENAR 2020 the LEITAP model (see par. 4.2) is used as such; part of the current SEAMLESS project is to develop iterative linkages between CAPRI and the GTAP model (see par. 4.1) (Jansson, 2008b)

3.3.2 Treatment of bioenergy

In its current version the CAPRI model distinguishes first generation biofuel feedstocks (mainly cereals and oilseeds), by-products (gluten feed) and biodiesel and ethanol based on fixed extraction coefficients. An extension of the model in order to better analyse processing of biofuels, as depending on energy policies and crude oil prices, is foreseen in a forthcoming study (Becker, 2008). Adaptation of the model refers to (a) the introduction of a biofuel processing industry, as a separate activity in the market module; with demand functions for feedstock, supply functions for (first generation) bioethanol and biodiesel and for by-products (several types of feedstuff); and (b) biofuel trade. Biofuel demand will be determined exogenously (based on policy driven demand scenarios), or derived from a linkage with an energy market model (like PRIMES). Results of this study are not available yet.

3.3.3 Data reliability

As already noted, the CAPRI data bases primarily rely on official EU and FAO statistics, which in turn are based on extensive national data sources. Data, needed to apply the biofuel model extension, are still to be collected.

3.3.4 Treatment of land use impacts

Total agricultural acreage, including non-used lands like set aside areas, are exogenously fixed in the CAPRI model. Within this total acreage, the model treats changing land use with considerable detail (regional level). Moreover, the CAPRI model enables post model calculations which downscale outcomes to a 1x1 km grid level.

3.3.5 Treatment of GHG-balance and biodiversity impacts

As noted above, post-model calculations of a number of environmental parameters are a standard feature of the CAPRI model. Among them are emissions of non-CO2 greenhouse gases. Extension of this feature is announced, as a part of the biofuel extension of CAPRI (see par. 3.3.2). This would include CO2 emissions from agricultural production (Becker, 2008). It is not clear whether also carbon sequestration by agricultural and/or forestry practices will be covered, nor whether GHG-emissions will be integrated within the model equations (allowing for assessment of impacts from climate policies like cap and trade regimes).

The CAPRI model provides an exception to the rule that PE (and GE) models do not assess biodiversity impacts: some biodiversity indicators are included in the post-model calculation matrix.

3.4 USA's International FAPRI model

3.4.1 General features

The Food and Agriculture Policy Research Institute (FAPRI) was established in 1984, as a cooperative research program of two academic research centres, the Center for Agricultural and Rural Development (FAPRI/CARD) at Iowa State University and the Center for National Food and Agricultural Policy (CNFAP) at the University of Missouri-Columbia (FAPRI-MU). It was financed by the US Congress. Providing US Senate and House with impact-analyses of agricultural policies belongs to the main objectives of FAPRI.

A number of separate, but interlinked models for agricultural commodities like grains, oilseeds, sugar, dairy etc. were developed to foster such analyses, either orientated towards US agriculture (mostly by FAPRI-MU), or covering global agricultural markets (mostly by FAPRI/Card). Together they constitute a coherent and widely renowned modelling system, called the 'international FAPRI model', the 'FAPRI Agricultural Outlook Model', or shortly 'FAPRI model'. Besides its most renowned modelling system, FAPRI's model portfolio includes a number of other, less comprehensive or sophisticated models (e.g. omitting dynamic features), which are used for provisional assessments.

The international FAPRI model stands for a (recursive) dynamic, multi-market, partial-equilibrium model. It distinguishes 20-30 primary and secondary agricultural commodities and 30-40 countries/regions (or less, depending on the commodity), together covering global food, feed and (bio)fuel production and markets.
Competition for land among crops is modelled by equations which relate land allocation to relative agricultural prices. Moreover, total agricultural area is expressed as a function of real prices (within certain exogenously set physical constraints)[10]. Productivity increases, price elasticities etc. are derived from (yearly reassessed) historical trends. Consumption depends on real and relative prices, as well as exogenous drivers like population- and GDP-growth. Finally, import and export are driven by positive of negative gaps between the autarkic (cost-)price and the world price, after accounting for transport costs and import tariffs.
The model is solved simultaneously for all commodities/countries by adapting prices, volumes and stocks in a recursive manner (ending stocks are next year's beginning stocks). In this way, not only prices, production- and consumption-volumes, but also agricultural land-use (by commodity and by country) is determined as endogenous variable of the model.

Key application of the international FAPRI model is the US and World Agricultural Outlook, published annually and presenting baseline projections over a ten year horizon. Next to this, the international and other FAPRI models are applied frequently to analyse impacts of policy proposals and other scenario's, starting from this baseline. Such analyses are often performed on request of US Senate or House members; they are published either as CARD-reports or as FAPRI-MU (before June 2007: FAPRI-UMC) reports.
Recently, a number of reports are issued, analysing the impacts from the emerging biofuel (ethanol) production and biofuel-related policies on crop markets, food and feed prices etc. To facilitate such analyses, the FAPRI model inventory was extended by an international ethanol model, including country modules for the US and Brazil (Tokgoz and Elobeid, 2006), as well as a national ethanol model (Thompson et al, 2008). Later on, country modules for EU, China and India were added to the international ethanol model, and model specifications were improved.

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[10] The precise specification of these and other equations is not clear from the sources, evaluated here.

Here, we take two of FAPRI/CARD´s most recent reports (Fabiosa et al, 2009; Dumortier and Hayes, 2009) as reflecting FAPRI's state of the art regarding bioenergy assessments. For a better understanding of FAPRI's model features we will also refer to some preceding publications.[11]

3.4.2 Treatment of bioenergy

FAPRI's bioenergy assessments are usually confined to biofuels, or – more precisely – to first generation bioethanol, used as additive to conventional gasoline, or as low-level ethanol-gasoline blend; sometimes high level blends are added as a third component of demand. Second generation biofuels, nor biodiesel used to be considered, because they are seen as non-competitive within prospected timeframes. In other words, the possibility of technological improvements and/or supporting policies in case of second generation biofuels, respectively their reality in case of European biodiesel is not perceived in FAPRI's reports.

Fabiosa et al (2009) apply the international FAPRI model, extended with a new component named 'international ethanol model'. This new component, as described by Tokgoz and Elobeid (2006) [12], includes the following key elements:

- Brazil is considered to dominate the international ethanol market, by defining the Brazilian ethanol price as the representative world ethanol price. Domestic ethanol prices in other countries are linked with the Brazilian price, adjusted for exchange rates, transportation costs, domestic subsidies and other policies. The US is the only exception, reflecting its nearly insulated ethanol market as a result of high import tariffs.
- Brazil's industrial ethanol capacity is not modelled. Neither are industrial production costs or revenues from by-products.
- Instead, Brazilian ethanol supply is directly linked (by a fixed conversion rate) to the share of cane, used for ethanol production. This share depends on the price ratio between ethanol and sugar, while cane production itself reflects harvested area and yield. The yield equation is not specified. The cane-harvested area equation comprises several factors, representing (a) cane area in preceding years (cane is a perennial crop), (b) prices of ethanol and sugar and (c) the price of competing crops (soy is considered as such).

  In other words: ethanol supply reflects profit maximizing choices by cane producers; the industrial part of the ethanol production chain is largely ignored.
- Brazilian ethanol demand is modelled by two equations, representing demand for anhydrous ethanol (used for 'gasohol', i.e. low-level blends), respectively hydrous ethanol (used as pure ethanol or high-level blend). Both equations include variables representing prices of ethanol and gasoline, GDP and population; besides there are variables capturing specific Brazilian features, namely the high share of flex fuel vehicles in the car fleet, and supportive policies (gasohol mandates).
- The US country module does model capacity growth of ethanol plants, as a function of *expected* demand during five years ahead (exogenously fixed), but on the condition that last years net returns (including capital costs) were positive; if not, capacity-growth falls to zero. Next to this, a utilisation rate is modelled, depending on existing capacity and net returns (excluding capital costs) in the current year. Net returns on their turn depend on the price of ethanol, revenues from by-products and costs of feedstock (corn) and energy, used in the production process.
- Ethanol demand in the US is modelled in a complementary relationship with gasoline demand (a higher price for oil results in lower demand for gasoline ánd ethanol). This reflects its main use

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[11] FAPRI/CARD papers tend to report incompletely on methods used; this hinders to some extent our evaluation.

[12] Tokgoz and Elobeid (2006) specify country modules for US and Brazil. According to Fabiosa et al (2009), country modules for EU-25, China and India are added (but not specified in their paper), while Japan, South Korea and a 'Rest of the World'-aggregate are represented by net trade equations.

as an additive/low-level blend. Fabiosa et al (2009) also evaluate a future penetration of flex fuel vehicles, resulting in a demand for high-level blends as a substitute for gasoline (in this case rising oil prices result in a lower gasoline- but higher ethanol-demand). Both demand components also depend on the ethanol price, supporting policies (mandates, ethanol producer support), and as usual GDP and population.

- Ethanol trade is modelled by an equation representing transportation costs and the high US import tariff (besides, a specific equation accounts for Caribbean countries which for certain quotas are exempted from this tariff). The equation results in zero imports, as long as the world price for ethanol plus tariff and transportation costs exceeds the domestic US price. If lower, than imports will oust domestic production and force the domestic US price to fall.

As a result, equilibrium prices and quantities of bioethanol are predicted by the model for the US, Brazil and elsewhere. Also changing prices, quantities and trade patterns of other agricultural commodities are predicted, as they are related through e.g. the sugar market and crop markets (embracing food and feed commodities).

The model enabled Fabiosa et al. to analyse different scenarios, such as introducing exogenously a demand shock in the US, respectively in Brazil/China/EU/India. Future applications may focus on the effects of different policy options to support bioethanol use.

3.4.3 Data reliability

The international FAPRI model has a long-standing reputation as one of the most reliable agricultural sector models for market outlook and policy analysis. It relies extensively on econometric calibrations, which are annually updated based on data from various sources (like USDA-FAS, FAO and IMF).

Clearly, its reliability is less, regarding new markets like biofuels and/or countries other than the US, due to data and/or experience limitations.

3.4.4 Treatment of land use impacts

The international FAPRI model treats allocation of agricultural land as the outcome of farmer choices, assuming that farmers maximize their net return per hectare. Typically, a FAPRI land supply equation for a specific crop includes variables indicating (a) actual (or last year-)acreage; with lagged effects, especially in case of perennial crops, (b) the price of the crop and (c) the price of competing crops. These equations enable to predict land use changes within total crop area. Shifts from pasture to crop area or vice versa are captured in the same manner.

Allocation effects, caused by increasing biofuel (ethanol) production, are not restricted to the producing country. E.g. Fabiosa et al. (2009) show how expansion of US bioethanol production causes multiple effects: within the US land moves away from crops like soy towards corn; corn ánd soy exports decrease; and their prices rise. These higher prices transmit worldwide, and so induce indirect land allocation effects elsewhere, in a country-, crop- and time-specific way.

The international FAPRI model, including the ethanol-modules, is capable to capture such effects. It enables to compute so called ‘impact multipliers’, which show the sensitivity of agricultural land allocation in all countries, if bioethanol use expands in one, e.g. US or EU. These impact multipliers are expressed as a unitless parameter (elasticity), indicating increase/decrease of land devoted to a specific crop in a specific country (in percents), as a result of one percent increase in ethanol use in one country.

Moreover, Fabiosa et al. (2009) also report on impact multipliers, regarding total crop area. It is not clear, however, whether these multipliers only indicate conversion of (agricultural) grassland into cropland and cultivation of set-aside land, or also conversion of non-agricultural land like forest area.

3.4.5 Treatment of GHG-balance and biodiversity impacts

Up till now, the international FAPRI model does not support analysis of impacts from bioenergy production on biodiversity or the greenhouse gas-balance. However, very recently a new extension of the model is presented, which aims at quantifying GHG-emissions from agriculture, including carbon stock impacts due to land use change (Dumortier and Hayes, 2009).

The present, preliminary version of this ‘Greenhouse Gases from Agriculture Simulation Model’ (GreenAgSiM) module is conceived as a post model-supplement to the FAPRI model. It calculates for each country:

(1) direct GHG-emissions (methane and nitrous oxide, from (ruminant) livestock, manure, tillage, rice paddies etc);
This is done by multiplying prospective crop acreage and livestock numbers (taken from FAPRI simulations) with default emission-coefficients (taken from literature).

(2) GHG-emissions from changing carbon stocks – biomass and/or soil organic carbon –, in case of forest and grassland conversion into cropland (respectively carbon sequestration in case of abandoned cropland, returning to natural vegetation);
This is done by multiplying the prospective cropland expansion or decrease (as predicted by FAPRI simulations) with a country specific carbon stock parameter. These parameters are computed as a weighted average of sub-national[13] coefficients, based on data (taken from literature) on ecological zones, types of vegetation and soil, and the like; while weighting factors depend on the assumed sub-national distribution of cropland expansion (or decrease).

Dumortier and Hayes contend that their GreenAgSiM module, applied as a supplement to FAPRI-simulations, makes it possible to assess the (direct and indirect) impact of different policy scenarios on global greenhouse gas emissions. This of course depends on the reliability of FAPRI-projections, especially regarding land use changes, and on the reliability of emission coefficients and carbon stock parameters, applied within GreenAgSiM.
Interestingly, Dumortier and Hayes foresee that future versions of their module will be more integrated within the international FAPRI model, allowing for feedback from this module into the main model. This would enable to evaluate, for example, the impact of a GHG-cap-and-trade system (including agriculture) on agricultural production.

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[13] Dumortier and Hayes confine themselves to the first administrative level within countries (e.g. states).

3.5 IFPRI's IMPACT model

3.5.1 General features

The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) was built in the early nineties by the International Food Policy Research Institute, with the ambition to provide policy makers long term (2020 and beyond), global insights on food supply, food demand and food security perspectives (Rosegrant et al., 2008a and b).

The IMPACT model is a recursive dynamic partial equilibrium model of the agricultural sector, with global coverage and substantial disaggregation. Originally it distinguished between 36 countries-regions and approximately 20 agricultural (primary) commodities. Ongoing research expanded the number of regions to 115, and the number of commodities to 40 (including fishery products from capture as well as aquaculture). An important change in the model structure was the introduction (around the year 2000) of a water simulation module (WSM), interacting with the primary IMPACT model in an iterative way (see below). The module is specified for 126 river basins around the world. Their intersection with regions resulted in a still finer disaggregation of 281 'food-producing units', each with own supply and demand functions.[14]

Annual commodity *supply* is estimated for each region (resp. 'food-producing unit') and each crop, as the product of harvested area and yield per hectare. Area- and yield response functions specify producer behaviour: his area response depends on elasticities, related to the crop's own price and prices of competing crops (both effective producer prices), and two corrective factors - one (exogenously determined) factor reflecting growth/shrinkage of agricultural area, and the other reflecting water availability (derived from the WSM module); his yield response depends on elasticities related to the crop's own price, and prices of factor inputs (labor and capital; not land), and again two corrective factors - one (exogenously determined) factor reflecting productivity growth, the other reflecting water availability (derived from the WSM module).

Supply of livestock commodities is modelled similarly, except that (1) the area response function is replaced by a 'numbers slaughtered' function, depending on own and cross price elasticities, prices of intermediate inputs (feed), and a exogenously determined growth factor; (2) the yield (per head) function only depends on expected productivity growth, not on factor-prices; and (3) water availability is not considered relevant.

Domestic commodity *demand* is estimated per region/crop, as the sum of its demand for food, feed, other uses and (in recent applications) biofuels. Food demand is modelled as a function of the commodity price (crop, livestock product, fishery product), prices of competing commodities (both consumer-prices), per capita income and total population; connected by elasticities. Country-specific income and population growth rates are exogenously introduced. Feed demand is a derived demand, depending on livestock commodity supply, feed ratio's, prices of feed crops and a technology improvement parameter (feed efficiency). Demand for 'other uses' is estimated as a fixed proportion of food (only crops) and feed demand. Demand for biofuel-feedstocks, at last, is modelled as a function of government blending mandates, (fossil) energy price and producer subsidies, but its specification is not clear from the sources, studied here.

Commodity prices are endogenous in the model, with domestic prices related to world prices by functions which reflect tariffs and other subsidies (expressed together in terms of producer and consumer subsidy equivalents) and a marketing margin (including transport costs). The model is

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[14] Nowadays both the original IMPACT model (without the water simulation module) and the IMPACT-WATER model (with this module) are applied, depending on the issues at hand.

solved at a yearly basis by determining a series of prices and quantities of all commodities at which all markets clear, including (minimized) net trade[15] between exporting and importing countries. Exogenous trends and/or shocks drive the shift towards new equilibrium from year to year.

In case of applying the IMPACT-WATER model, this solution procedure includes iteration with the outcomes of the water simulation module (WSM). As noticed above, WSM results enter into the area and yield response functions of crop producers: in case of water shortage, they may face less than optimal yields; they also may decide to diminish irrigated area or to diminish certain crop areas, in favour of crops less sensitive to water stress or leaving part of their land fallow.

The water supply module itself firstly assesses water availability, on a yearly basis, for agricultural, industrial and domestic uses, respecting minimum levels with regard to navigation and environmental/ecological requirements (such as salt leaching). This assessment follows a (hydrological) water balance approach for each water basin, including rainfall, linkages between water basins etc. Also expected changes, such as long term climate change effects on rainfall can be addressed, as are different hydrological time series to explore impacts of water supply uncertainty.

Then the available water supply is allocated, with first priority to domestic water demand, second for industrial and livestock demand, and third priority for irrigation demand (crops). Allocation of water for irrigation between the main crops in a basin is optimized on a monthly basis, depending on the profitability of crops, their irrigation water demand and their sensitivity to water stress.

The iteration procedure starts with running IMPACT, assuming no water shortages, for the whole prospective period (e.g. 20 or 30 years); delivering equilibrium prices and quantities if water availability is taken for granted. Then WSM is applied for the same prospective period, with agricultural water demand derived from the first IMPACT run, and eventually resulting in restrained water availability for agriculture (irrigation). If so, this is input for a second IMPACT run, leading to adjusted prices and quantities. And so on, till after some iterations equilibrium prices and quantities, *including* expected water shortage effects, are found.

A final feature of IMPACT concerns the relation between food supply and demand, and food security. The percentage of malnourished young children (under the age of 5) is used as food security indicator. The model is able to assess this percentage through post-model calculations, based on a mathematical relationship[16] between child malnourishment and four variables: average calorie consumption per capita, female access to secondary education, quality of maternal and child care, and health and sanitation. Data on the first variable come (mainly) from IMPACT; data on the other three variables come from other sources (WHO, FAO, Unesco, World Bank etc.).

3.5.2 Treatment of bioenergy

As noticed above, feedstock use for bioenergy production is distinguished as a separate category of demand in recent IMPACT applications. This refers to agricultural commodities like maize, wheat, sugar cane and oilseeds, used for first generation biofuels only. Biofuel production itself has not been modelled, as the IMPACT model is largely confined to primary agricultural commodities[17], nor is biofuel trade. We also noticed earlier that biofuel demand functions are not specified. In fact, the

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[15] Only *net* trade, as Armington assumptions are not included in the IMPACT model.

[16] These variables were found relevant in earlier IFPRI research, based on regression analysis of child malnutrition and its causes in 63 developing countries during the period 1970-1996 (Smith and Haddad, 2000).

[17] The model does distinguish (oil-)meals as commodity used for feed, but we did not found indications that by-products from biofuel production are included here.

focus is on analyzing supposed policy driven scenarios with exogenously determined levels of biofuel production, and their possible impact on food prices.

3.5.3 Data reliability

IFPRI uses a number of data sources, like national and UN statistics, as well as own data compilations, to underpin model calibration/validation and baseline scenarios. However, elasticities and other parameter values are not very well documented, especially not in specific model applications like bioenergy assessments. E.g. Rosegrant et al. (2008b) note that the model was (re-) validated, based on production trends in the years 2000-2005 (including biofuel developments), the result of which is loosely described, saying that the (recalibrated?) model captured "… a significant amount of the increase in real prices for grains during this period."

Our short analysis does not allow a more extensive evaluation of data/parameter reliability of the IMPACT model.

3.5.4 Treatment of land use impacts

The IMPACT model treats direct land use effects in terms of shifts between crops, as farmers optimize their land use. Such allocation effects transmit worldwide, as a result of shifting trade patterns of agricultural commodities.

Possible indirect effects in terms of shifts between agricultural and non-agricultural land are not captured, as total agricultural land in each country/region (resp. 'food-producing unit') is fixed (except reacting to a exogenously determined trend factor, reflecting non-agricultural land use dynamics).

Possible effects on land productivity are sometimes analysed (by exogenously adapting the productivity growth factor in the yield response function; e.g. Rosegrant et al., 2006), sometimes not (e.g. Rosegrant et al., 2008b).

3.5.5 Treatment of GHG-balance and biodiversity impacts

Environmental impacts of different scenarios, like on GHG- balance and biodiversity, can not be assessed by the IMPACT model.

3.6 IIASA's GLOBIOM and TAMU's ASMGHG models

3.6.1 General features

The 'global biomass optimisation model' (GLOBIOM) was developed in recent years by IIASA, as a global, recursive dynamic PE model, covering the agricultural, forestry and bioenergy sectors in an integrated way. The precise structure of this new model is not publicly available yet (see Havlik et al, forthcoming), but is described to be similar to the concept and structure of the ASMGHG model, developed at Texas A&M University (Havlik, 2009). So, we shortly characterize this model first.

In several respects the 'US agricultural sector and mitigation of greenhouse gas' (ASMGHG) model, as described by Schneider et al., 2007) is a peculiar PE model:

- It is based on mathematical (linear) programming, but includes economic optimisation in its objective function. Numerous agricultural management practices are specified in separate (Leontief like: fixed quantities of multiple inputs and outputs) production functions, for 63 US regions (mainly States), regarding some 40 crops, livestock and forestry products. These functions represent as many agricultural and (commercial) forestry production 'technologies', depending on soil types, tillage, rotation, fertilisation and irrigation alternatives etc. (crops and forestry), production intensity, diet alternatives, manure treatment etc (livestock), processing technologies (processed commodities); each relevant combination having its own function. Productivity increases within each technology are not modelled. For each US region also natural and human resource endowments are specified. The same characteristics are documented for 27 regions outside the US, but restricted to 8 major crops. For all other crops, livestock and forestry, there is only one 'rest of the world' region besides the US.
- Farmers and foresters are able to choose between production technologies and to increase or decrease factor inputs, but only within constraints. Regarding *technologies*, possible choices are constrained by historical practices (crop mixes, lifestock mixes, farming intensity etc.) during the last 30 years in each region, assuming that these practices represent rational behaviour of farmers, reflecting resource availability, weather conditions, crop rotation considerations etc. These constraints impose an implicit cost for deviating from historical experience. Crop mix constraints are nót applied, however, to crops which may expand far beyond historical shares; e.g. second generation energy crops like switch grass, poplar and willow.
  Regarding *factor inputs,* land use changes (between traditional crop area, pasture, energy crops, permanent forest) are constrained by land suitability (derived from GIS data) and ultimately by given regional endowments.
- Given such constraints, the ASMGHG model optimises quantities and prices of factor inputs and commodity outputs, by interaction between (constant elasticity) supply and demand functions, reflecting (only?)[18] the own price elasticity of each commodity or input factor (prices for some input factors, i.e. energy, are determined exogenously).
  The model is solved by determining prices and quantities which maximise 'total agricultural sector based surplus' in each region (including surpluses from agricultural trade with other regions); that is the sum of total consumers' surplus, producers' surplus and governmental net payments to the sector, minus total cost of production, transportation and processing.
- The ASMGHG model also contains a number of environmental impact accounting equations, which enable to assess especially climate change impacts: direct and indirect emissions of CO2 and other greenhouse gases (like methane, N2O), including emissions from fertiliser use, land use change, sequestration by afforestation etc. This set of equations contain emission and sequestration coefficients, taken from literature. It not only serves as a post-model accounting

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[18] This is not clear from Schneider et al. (2007), neither is the underpinning of chosen elasticity values.

module, but also enables to evaluate policy impacts: if, i.e., a carbon price is introduced exogenously, its impacts are included in the optimisation process, resulting in endogenously adapted prices and quantities, land use change, GHG emission reduction and increased sequestration; all in optimal proportions, given this carbon price.

Available information (Havlik, 2009)shows that IIATA's GLOBIOM model not only resembles the ASMGHG model, but also deviates:

- GLOBIOM is announced as a recursive dynamic model for long term assessments, whereas ASMGHG shows up as a comparative static model, computing medium term equilibrium outcomes after exogenously introduced shocks;
- GLOBIOM has much more geographical detail: 200.000 'simulation units', delineated by combining 0,5⁰ x 0,5⁰ grid cells and country borders; grouped into 27 world regions. Simulation unit data come from biophysical models (like EPIC), global mapping of crop and forest productivity, global mapping of carbon sinks (soils and biomass) etc.
- Sectoral detail in GLOBIOM seems comparable (forestry, energy crops), or confined (agriculture: only main crops, no livestock) compared with the ASMGHG model.

3.6.2 Treatment of bioenergy, land use and GHG-balance impacts

The GLOBIOM model, and the ASMGHG model as its precursor, are especially designed to analyse GHG-balance impacts, related to land use; be it from agricultural practices, commercial forestry, bioenergy feedstock production (first and second generation) or from land use change (see above). A special characteristic is their integrated approach, trying to cover both carbon stocks and streams. In this way, in principle all GHG-relevant aspects of land use are included; i.e. (referring to forestry) deforestation ánd afforestation ánd forestmanagement.

A limitation of these models is their confinement to land using sectors. Bioenergy *processing and using* sectors for example, like motorfuel/transport and energy (electricity) generation, are not included, neither are endogenous energy prices. This limitation implies that carbon- (resp. GHG-) related shifts only result from exogenously introduced policy shocks or energy price shocks.

3.6.3 Data reliability

Insufficient information is available to comment on data reliability. This seems, however, a sensible aspect, given the heroic ambition to rely not only on very detailed, geographically explicit baseline data with global coverage (needed for calibration), but also to capture real world dynamics, triggered by market forces and behavioural responses of farmers and foresters.

4. Bioenergy analyses using general equilibrium models

4.1 The Global Trade Analysis Project (GTAP) model

4.1.1 General features

Without doubt, the ‘Global Trade Analysis Project’ (GTAP) model is leading in the field of economy wide, global models, used to analyse bioenergy growth and impacts. Purdue University’s Center for Global Trade Analysis started its development in the early nineties, as a double challenge: to design a model, suited to assess policy impacts at the global scale, considering all substitutions that might occur in the global economy; and to compile and regularly update an adequate database – ‘social accounting matrix’ (SAM) – needed to run and to calibrate such a model.

The GTAP-Purdue team succeeded in this endeavour by implementing a cooperative, ‘open source’ attitude. First, the ‘standard GTAP model’ was designed, as a general equilibrium model with rather classical features (Hertel (ed), 1997).[19] Building on this workhorse, the Purdue team developed more advanced and/or extended versions of the model (e.g. a recursive dynamic version), while at the same time encouraging other researchers to design ‘offspring’-models, adapted and improved according to their needs.

In the same vein the GTAP-database was built and is renewed every 2-4 years in cooperation with a number of (mainly institutional) data providers; moreover – not its least attraction – this database has been made publicly available. The actual GTAP-7 database (2008) covers input-output tables and bilateral trade data of 57 production sectors (respectively commodities, among them about 20 primary or processed agricultural commodities), within 113 countries/regions. It depicts the global economy for the year 2004.[20] All sectoral and country/regional data are identically structured, in order to facilitate any aggregation which might be preferred in the context of specific applications.

All in all, the ‘GTAP-family’ nowadays represents a worldwide, mutually inspiring community of researchers, applying and further developing several versions of the GTAP model and its offspring, and/or using the GTAP database (see par. 4.2).

As a general equilibrium model, the GTAP model embraces all markets, including factor markets (land, labour, capital), in a mutually dependent way. Starting from a base-year with an exogenously introduced, disturbing ‘shock’, e.g. a supposed new government policy, the model searches for a solution – ‘model closure’ – in which supply and demand on all markets equilibrate; it does so in an international setting with bilateral trade. In other words, the model detects the prices and quantities which match with this equilibrium.

As a static model, GTAP only predicts this possible outcome, after – generally speaking – some 20 years of adaptation following the initial disturbance. Adaptation processes may include e.g. technological change, substitution of primary production factors, changing trade patterns, but how such processes pass on, is not predicted by GTAP.

In GE-models, producer’s and consumer’s capacities and preferences to adapt, are modelled as substitution elasticities (indicated with ‘σ’). For producers, such elasticities and their coherence can be depicted as a tree-like ‘production structure’, piled up from several ‘nests’ with production

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[19] According to Van Tongeren (2001) the GTAP model typically shows up as a ‘first generation’ GE-model; see par. 2.

[20] GTAP databases 5 and 6, depicting world economy in 1997 respectively 2001 are still widely used.

inputs of divergent substitutability. All inputs are measured in value terms. For consumers 'consumption structures' can be pictured in a comparable way.[21]

Figure 4.1 shows the typical production structure in the standard GTAP model (elasticities are indicated with the symbol 'σ'). It represents a basic assumption of this model, namely that producers are able to substitute primary production factors in case of changing factor prices ($\sigma \neq 0$, in the 'value added nest'), but are not able to substitute primary factors for intermediate inputs or vice versa ($\sigma = 0$, between the 'value added nest' and the 'other inputs nest'). The only choice regarding intermediates is between domestic and foreign inputs.

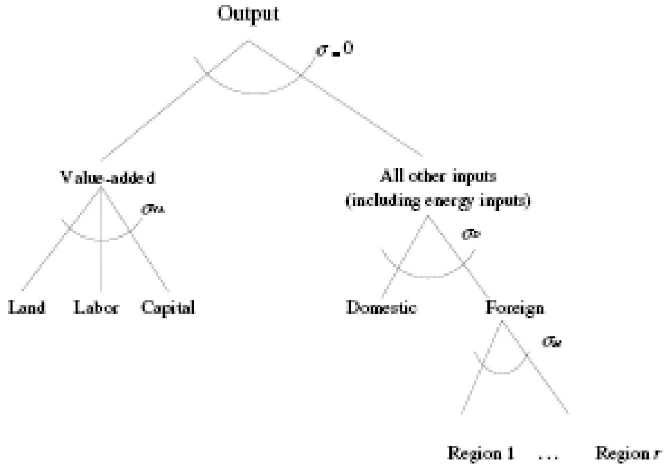

Fig. 4.1 Production structure in the standard GTAP model (Source: Burniaux and Truong, 2002)

From figure 4.1, virtually multiplied to all producers and consumers, it is obvious that elasticities are a crucial model parameter: they determine how the effects of a 'shock' (initial disturbance) spread through the whole economy, provoking adaptations which eventually lead to a new equilibrium. The value of GTAP-elasticities are partly derived from historical analysis (calibrations, using the GTAP-database), partly taken from literature.

One important field of GTAP applications has always been (and still is) climate/energy policy, including assessment of GHG-emissions and emission abatement. In view of this problem area, extended versions of the GTAP model were developed by the Purdue team (GTAP-E, GTAP-AEZ, GTAP-BIO) as well as by others (see par. 4.2); databases are extended accordingly. We will discuss these versions here to some extent, with a focus on bioenergy and related climate impacts.

4.1.2 Treatment of bioenergy

The GTAP-energy and environment (GTAP-E) model was introduced in 1999 (Truong, 1999), was fully unfolded in 2002 (Burniaux and Truong, 2002) and technically further improved in 2008 (McDougall and Golub, 2008). We refer to the 2002-version.

GTAP-E is an extended version of the standard GTAP model, with energy-factor substitution and inter-fuel substitution as new features. Substitution between energy and primary production factors (notably capital or labour) deals with energy conservation. Inter-fuel substitution deals with choices

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[21] Production and consumption structures correspond with linear supply and derived demand equations of firms, respectively demand equations of consumers; see e.g. Birur et al. (2008).

between electricity, coal, oil, gas, petroleum products; all of them distinguished with regard to domestic or non-domestic origin.
Technically this was done by changing the sector production structures as depicted in figure 4.1: ‘Energy’ was taken out of the intermediate input ‘nest’ and incorporated in the ‘value added nest’, forming a capital-energy composite (including substitutability). At the same time ‘energy’ was decomposed, by adding extra ‘nests’ to the production structure, representing substitutability between different fuels (compare fig. 4.2; note that biofuels were not distinguished in GTAP-E; see below). Comparable restructuring was carried through in relevant consumption structures.

Elasticity values were determined, assumed to reflect the preferences (expected behaviour) of producers and consumers. Furthermore, the database was enriched with a carbon module, containing emission coefficients for all fuels. In this way, GTAP-E enables to analyse the economic impacts and environmental effectiveness of e.g. carbon/energy taxes or cap and trade instruments. The GTAP-E model clearly represents a step towards a modelling framework, suitable to analyse climate/energy issues. However, bioenergy (and other renewables) were not recognised at the time, so were not distinguished separately.

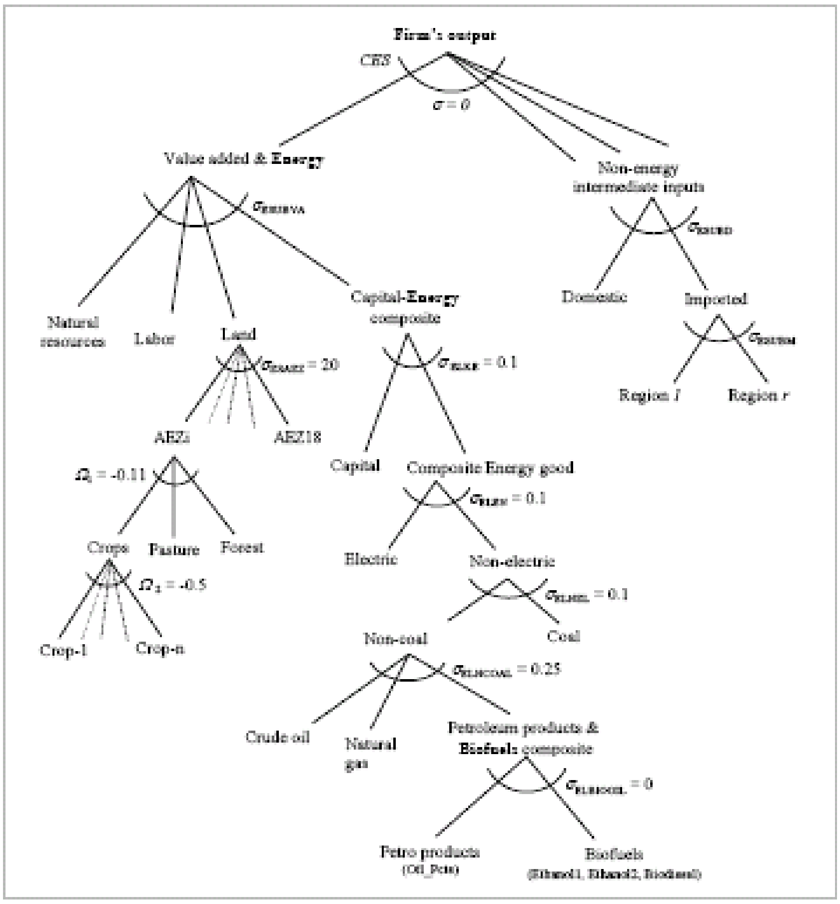

Fig. 4.2 Production structure in the GTAP-BIO model (Source: Birur et al., 2008)

Recently, a substantial modification of the GTAP-E model was presented, sometimes nicknamed GTAP-BIO (Birur et al, 2008), in which first generation biofuels (bioethanol, biodiesel) are explicitly modelled, as are land use impacts from biofuel production.[22] Four modifications, compared with GTAP-E, seem most important (see also fig. 4.2):

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[22] The modelling of land use impacts builds on another GTAP-extension, namely GTAP-AEZ. We discuss this extension in par. 4.1.4.

- Three biofuel production sectors (ethanol from cane, from cereals and biodiesel) are distinguished, with production structures/supply equations comparable to other sectors; however, biofuel by-products are not specified.
- Consumption structures/equations (household demand) are modified to allow for choosing biofuels (low-level blends), represented by a relatively high substitution elasticity vis-à-vis conventional motorfuels;
- Use of biofuels as an additive is captured by modifying the production structure of firms (extra 'nest', with $\sigma = 0$; allowing to model obligatory use);
- Land endowments in each country/region are split up according to Agro Ecological Zones (AEZ's; see par. 4.1.3).

The aim of the GTAP-BIO model is not only to analyse the economic impacts of (first generation) biofuel production, but also to assess the expected replacement effects in terms of resulting land use shares within Agro Ecological Zones.

4.1.3 Treatment of land use impacts

Land is modelled in the standard GTAP model as a homogenous, non-tradable endowment of regions/countries, used as a primary factor input in land-based sectors (mainly agriculture) which produce different crops, livestock (pasture) etc. Land substitution[23], or 'transformation' is modelled by CET (constant elasticity of transformation) revenue functions. Such functions assume that landowners use their parcels of land as to maximize rental revenue.[24] The transformation elasticity (identical for all agricultural uses) is based on econometric (US-) evidence.

In reality however, types of land differ, e.g. regarding their suitability for certain uses, their productivity (yields) and GHG-related properties. Lee (2004) pioneered incorporating these aspects in GTAP. Hertel et al. (2008) present a fully developed model extension: GTAP-AEZ. Essential modifications, compared to the standard GTAP model, are as follows.

- the homogenous input factor 'land' is replaced by heterogeneous land endowments, according to 'Agro Ecological Zones' (AEZ's)[25]. As before, these endowments are measured in value terms. Base year endowments are determined by combining geographical information (AEZ's, land cover) and agro-economic information (total land rents by crop/pasture in each country/region). Commercial forestry is by definition confined to 'accessible' forest area (i.e. within certain distance from infrastructure, and/or privately owned); related rental revenue is derived from sold timber.
- land competition is diversified, via a three level nesting structure, respectively representing competition between different crops; between crops and pasture; and between agriculture as a whole and commercial forestry; each nest has its own CET transformation elasticity. The equations also represent expected long term yield improvements, derived from (global) literature.

This extended framework enables to integrate competition between and conversion into types of land as distinguished in the GTAP-model. It also enables to distinguish between the so called

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[23] As already noted, land – like all production inputs – is measured in value terms, based on the rental revenues from its use. This implies that also land transformation is not expressed in pure hectares, but in hectares converted into their rental proceeds.

[24] A distinctive feature of these CET functions is that additional land supply for a certain use becomes less attractive along with a growing share of this use in the total land endowment.

[25] The AEZ concept was developed by FAO/IIASA (2000). FAO/IIASA distinguish 18 AEZ's, by combining three climate zones (tropical, temperate, boreal) with six length-of-growing-period intervals (1-60 days; 61-120 days; etc). In Hertel et al. (2008) they are aggregated into six, by abstracting from climate zones.

acreage response and the yield response, in case of for example a biofuel demand shock exogenously introduced to the model: acreage response refers to changes in land use; yield response to substitution between factor inputs – land, capital, labor – resulting in higher productivity. Both responses will partly transmit across borders, depending on trade elasticities.

As mentioned above, Birur et al. (2008) take the GTAP-AEZ extension on board in their GTAP-BIO model. That is, they apply it in the context of the GTAP-E model. Some differences emerge however. Firstly, Birur et al. apply a two level nesting structure for land competition, with competition between crops at one level, and competition between crops, pasture and forestry at the other (see fig. 4.2). Secondly, Birur et al. apply CET-elasticities which are significantly lower in absolute terms than those of Hertel et al., indicating less easy reallocation of land between crops and between crop area, pasture and commercial forest. It appears that Birur's elasticities are based on more recent calibrations by Ahmed et al (2008), which however still are based on US data only.

4.1.4 Treatment of GHG-balance impacts

According to Hertel et al. (2008), the GTAP-AEZ extended model is well suited to analyse negative (emissions) and positive (sequestration) GHG impacts from land based sectors; not only from bioenergy related activities but from agriculture and forestry in general. Sequestration and emissions from these sectors – including land conversion – are obviously land (use) specific, as are related costs. For agriculture, Hertel et al. distinguish between emissions associated with factor inputs, like methane emissions from livestock capital or from paddy rice cultures; associated with intermediate inputs, like nitrous oxide from fertilizer; or associated with output, like CO_2 from agricultural residue burning. Emission coefficients and mitigation costs were taken from available engineering studies and calibrated for each AEZ.
For forestry these authors distinguish between land conversion (either positive: afforestation or less deforestation; or negative: increased deforestation) and forestry practices, like the choice of harvest age. Sequestration coefficients and related costs are taken from literature.

Hertel et al. present an illustrative application of the GTAP-AEZ model by investigating the GHG-impacts of a supposed unilateral (US-) carbon tax, in a context of international competition for land and other inputs, as well as on product markets (in this study only three regions – USA, China, Rest of the World – are distinguished, whereas AEZ's are grouped into six; as already noted above). They note that several relevant aspects are not yet included in the model specifications and related database, like soil carbon stocks and regionally differentiated mitigation costs. Nevertheless, the outcomes show how the impacts of this unilateral policy spread internationally (leakage effects) and partly materialize via land conversion, partly via improved practices in agriculture as well as forestry.
The GTAP-BIO model, with all AEZ's distinguished and more regional differentiation, appears as a suitable framework for more extensive investigation along these lines. One application is published very recently, on behalf of the California Environmental Protection Agency (Air Resources Board). Here, the GTAP-BIO model is applied to deliver GHG-emission coefficients of several biofuels, representing (worldwide) indirect land use effects, in order to assess their compliance with California's Low Carbon Fuel Standard Program (CEPA-ARB, 2009a, 2009b).

4.1.5 Data reliability

The GTAP database is renowned as one of the most extensive and reliable social accounting matrices, supporting GE model applications. However, regarding issues like land conversion, and forestry and agriculture related GHG mitigation, this database obviously has to contend with data limitations. Elasticities are crucially important, but especially in GTAP AEZ and BIO based on rather limited experience (few countries, short periods). Also the adequacy of certain equations in modelling behavioural choices of landowners and farmers/foresters is disputable. Therefore, further development and testing of the GTAP-BIO model and its database remains a challenge, and outcomes of model applications should be considered with great prudence.

Nevertheless, the model, given its present design and limited data quality, already demonstrates unmistakably the relevance of both acreage and yield response; as well as the occurrence of spill-over effects of GHG mitigation policies as a result of international trade.

4.2 GTAP offspring models

4.2.1 The Dutch LEITAP model

The LEITAP[26] model was developed by the Dutch Agricultural Economics Research Institute (LEI), part of the Wageningen University, as an extended version of the GTAP-E model (see par. 4.1.2). Essentially three modifications were introduced (Banse et al., 2008; Eickhout et al, 2008):
Firstly, biofuels were introduced in the production structure of the petroleum sector, in a way which is quite comparable to the GTAP-BIO model (see above), except that here only the petroleum sector structure has been adapted. Several biofuels are distinguished – biodiesel from vegetable oil and bioethanol from cane/beet, wheat of other grains; second generation biofuels can easily been included in this structure, but till now model applications are confined to first generation biofuels only. With this extension, the model is apt to assess impacts of policies like biofuel mandates or producer subsidies. However, contrary to GTAP-BIO, consumption structures are not adapted, nor are production structures of other sectors than petroleum. This implies that consumer preferences and related policies (like tax-differences), as well as intermediate biofuel use are not easily assessed with the LEITAP model.[27]

Secondly, land allocation is modelled quite differently compared with GTAP-E (and with the standard GTAP model, as the specification of this component was not changed in GTAP-E; see above). GTAP-E supposes agricultural land to be transformable between different uses, according to a CET function with uniform transformation elasticity. Total agricultural land use is exogenously fixed (in value terms; see par. 4.1.3). In the LEITAP model this simplified structure is replaced by a nested, three level structure for agricultural land use, as developed by the OECD in the Policy Evaluation (PEM) Model (OECD, 2003). Transformation elasticities in this structure differ, with $\sigma3 \geq \sigma2 \geq \sigma1$ (see fig. 4.3). So, some real world agro-economic features are captured, e.g. that it is easier to change land allocation between annual crops than between annuals/perennials/ pastures, while it is still more difficult to switch between horticulture, ‘other crops’ (like rice, fibers) and field crops (and ‘non-agricultural land’; this category is not included in OECD’s PEM model, but is added to the lower nest – ‘L NAG’ – by the LEITAP authors).

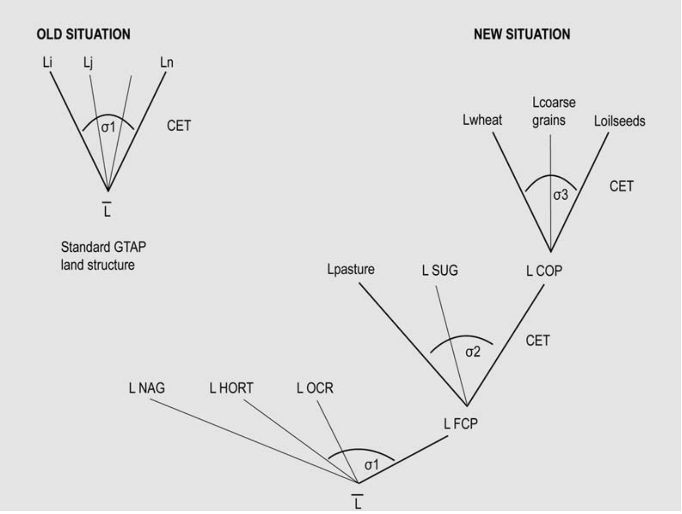

Fig. 4.3 Land supply structure in the LEITAP model (Source: Eickhout et al., 2008)

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[26] Sometimes also referred to as LEI-GTAP, GTAP-IMAGE, or LEITAP/IMAGE

[27] Banse et al. (2008) adopt the value of elasticities from literature, in fact from the GTAP-BIO authors. Surprisingly, the values found by Birur et al (2008), indicating consumer preferences in US, Brazil and Europe, are applied by Banse et al. as elasticities in the (petroleum sector) production structure in those countries.

This nested structure, using CET functions with different transformation elasticities, is comparable with the modelling approach in GTAP-AEZ and GTAP-BIO (see par. 4.1.3); except for two differences: Banse et al. distinguish between more agricultural land uses, but at the same time exclude the forestry sector. The implication of excluding forestry is that conversion of forest area into agricultural land (or vice versa) is not covered by the CET-structure in the LEITAP model. The third modification introduced by Banse et al. obviates this lacuna, as shown below.

Thirdly, the exogenously fixed total acreage in GTAP-E is replaced by a land market, on which land demand from agricultural production sectors meets land supply from landowners. Land demand and supply together determine actual agricultural land use, within some upper boundary of potentially available agricultural land; and at the same time they determine land prices (respectively rental rates). In this way, agricultural land use becomes an endogenous variable, able to contract (e.g. idling of agricultural land, conversion to non-agricultural use) or to expand (e.g. re-cultivating set aside lands, conversion of natural land, e.g. forest area).

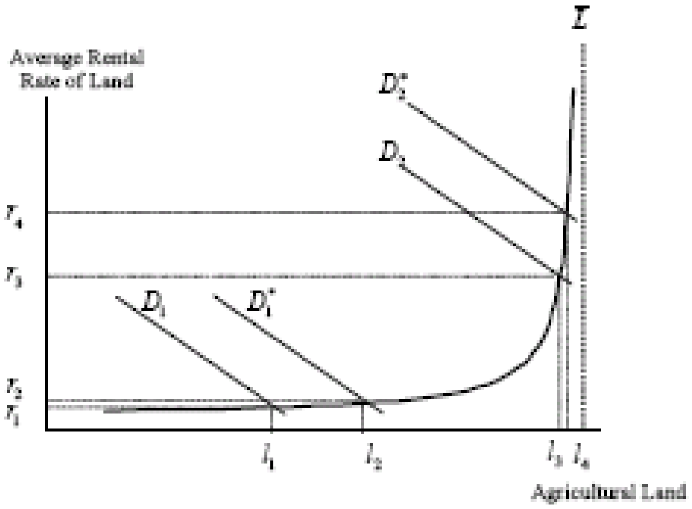

Fig. 4.4 Land-supply and -demand interaction in land-abundant (D_1) and land-scarce (D_2) regions. (Source: Banse et al., 2008)

The land supply curve (see fig 4.4) relates agricultural land use in a country or region to the average rental rate of land. The reasoning behind this curve is that a low average level of land rents reflects land abundance and/or relatively low agricultural product prices; is such situations only high productive/easily cultivable lands will be used. If product prices rise and/or land is scarce, also the rent level will rise, on average, and the utilisation of less productive/not yet cultivated land becomes attractive for landowners and farmers.

Obviously, the land supply curve will be country specific, as are actual supply and demand intersections: in land abundant countries, additional demand for land (e.g. as a result of rising biofuel demand) will lead to modest increases in land rents and substantial additional land use (see the shifting demand curve D_1 in figure 4.4). While in land-scarce countries the opposite effect can be expected (see demand curve D_2): substantially higher rental rates (and indirectly: intensification of agriculture), but no or hardly any land conversion.

In Banse (2008) the specification and calibration of this land supply curve is either based on historic land prices and land use data (Europe-15), or (all other regions/countries) on a proxy, because such data were not available. The estimated crop productivity of all $0,5^0$ x $0,5^0$ grid cells in a region/country, serves as a proxy (Eickhout et al., 2008; see for a discussion also par. 5.3).

4.2.2 The MIT-Emissions Prediction and Policy Analysis (EPPA) Model

The EPPA model is developed by the MIT (Joint Program on the Science and policy of Global Change), as a component of the Integrated Global Systems Model (IGSM). EPPA represents the human systems; other components represent earth systems (athmosphere, ocean, urban and land). EPPA has been used for a variety of climate related policy analyses, either as a IGSM component, or in stand alone mode. Its focus is on long term climate change and mitigation policies, with a time horizon of usually 100 years. In other words, the model is designed to scout long term impacts of major new policies, technologies and structural changes, not to predict with reasonable accuracy the state of affairs within a few decades.

The EPPA model in its actual, fourth version (EPPA-4, documented by Paltsev et al., 2005) is a recursive dynamic GE-model with bilateral trade features and global coverage. Production and consumption sectors are represented by nested CES-functions, as usual in GE-models; elasticities are based on own estimates (or ‘guestimates’), based on available literature including technology forecasts. The model is solved recursively at 5-year intervals, from 2000 till 2100.

The EPPA model uses the GTAP-5 database (base year: 1997) as its social accounting matrix (SAM). However, (1) GTAP regions and especially sectors are aggregated (e.g. about 20 agricultural sectors into one); (2) some climate-relevant sectors are disaggregated (e.g. one electricity sector into three: nuclear, hydro, fossil); (3) eight advanced energy technologies (like wind and solar, CCS – carbon capture and storage, and bioenergy) are added as (potential) new sectors, which enter the market place if and when they become economically competitive; and (4) data are added regarding resource bases (fossil energy) and greenhouse gas emissions (all sectors).

After these modifications EPPA-4, in its standard version, distinguishes 16 regions and 21 sectors. A distinctive feature of EPPA is that fossil energy resources are treated as depletable stocks, with diverging costs of exploitation and scarcity rents. This allows endogenic determination of fossil fuel prices. E.g. in EPPA’s reference scenario, the world oil price rises endogenously to a level in the year 2100 which is 4.5 times higher than the year 2000 price.

Two new technologies are bioenergy based: liquid (motor-)fuel and electricity, both produced from lignocellulosic biomass with advanced, not yet commercially viable technologies. It seems illustrative for EPPA’s long term focus, that current, first generation biofuels as well as proposed second generation biofuels (like lignocellulosic ethanol) are absent: their resource base is perceived too small and/or their greenhouse gas-balance too unattractive to expect a major role over the longer term. Both proposed technologies are characterized by guestimated production-functions and -costs, elasticities, energy-efficiencies and emission coefficients.

Reilly and Paltsev (2008) discuss several EPPA applications, showing the potential role of both advanced bioenergy technologies. Given the assumptions and guestimates in EPPA, bio-oil will become competitive from 2020 onwards and will gain substantial market share, even in the reference scenario. The prospected rising world oil price plays a decisive role here. Bioelectricity, however, is expected not to outclass coal based electricity, not even if the latter is combined with CCS technology. Climate policies, like cap and trade instruments (assuming that emissions from land conversion are excluded), are shown to strengthen the penetration (market share) of bio-oil. But at the same time they will hamper bioelectricity: land demand for bio-oil feedstock drives up the land price and raises the cost of bioelectricity further above competitive level.

With EPPA, land use impacts are assessed only to a limited extend, due primarily to the high level of sector aggregation: all crops, livestock and even forestry production into one agriculture sector. The implication is that land is treated as a homogenous input. Moreover, the EPPA model, like other GE-models, measures land in (monetary) values, not in (physical) hectares. So, the outcomes of EPPA applications regarding land are still in value terms, and may as well correspond to less, high productive hectares, as to more, low productive hectares. Therefore, Reilly and Paltsev present their calculation of land use impacts (in terms of hectares) as a first approximation. Finally, as an explicit warning, they point at the issue of land conversion, which is not assessed by EPPA, but may well represent additional carbon emissions which more than undo the savings from reduced fossil fuel use. Unless – as they suggest – agricultural and land conversion emissions are brought under a cap and trade regime.

4.2.3 The DART (Dynamic Applied Regional Trade)-model of IfW Kiel

The DART-model is developed in the late nineties by Kiel University (Institute for the World Economy) as a recursive-dynamic version of the (standard) GTAP model (Klepper et al., 2003), intended to analyse international climate change policies.

Recently the model has been extended to include (first generation) biofuel production (Kretschmer et al., 2008). This extended version of the DART-model uses GTAP-6 (with baseyear 2001) as its social-accounting matrix; it aggregates the global economy into 21 sectors (including 7 energy sectors and 11 agricultural sectors) and 21 regions (including 7 EU regions and major bioenergy producing regions: Brazil, Indonesia/Malaysia, USA). Compared with GTAP-6, some sectors were disaggregated using other data sources, in order to distinguish bioethanol, biodiesel and their feedstock crops. By-products from biofuel production are not distinguished however.
Bioethanol and biodiesel production are modelled as so-called ‘latent technologies’, i.e. technologies which were available in the base year but not active, due to non-competitive cost levels; waiting for activation by changing market forces and/or policies. Relevant market forces – like changing prices of conventional fuels and feedstocks, and technological improvements – are partly endogenous, partly exogenously fixed. Policies – like subsidies, tax exemptions, blending quota – should make up for the price difference (‘mark up’) with conventional fuels. These are exogenously introduced.

Kretschmer et al. (2008) present a first application of the model on EU biofuel policies, focussing on price- and welfare (GNP-) effects and the efficiency of the EU-climate policy package as a whole. Three scenario’s are evaluated: a reference path, including EU-targets for CO2-emission reduction (20% in 2020, relative to 1990 emissions), while EU-biofuel consumption stays at 2005-level; and two policy scenario’s, namely 10% biofuel use in each EU member state, with or without biofuel trade.
Kretschmer et al. (in press) add a more detailed evaluation, based on further differentiated scenario’s: no biofuel target, implementing the 10% biofuel target at member state- ór EU-level; yes or no combined with an additional renewable energy target (20% in 2020 at EU-level); economic optimization of emission abatement within ETS-sectors (emission trading) only or within the EU-economy as a whole.
Neither of these analyses present direct or indirect environmental effects. The first omission seems easy to repair, given the fact that the DART model enables to compute CO_2-emissions from energy use (Klepper et al., 2003). The second omission, however, reflects a structural limitation of the present model, as it does not treat ‘land’ as an independent primary factor but only as part of ‘capital’ (Klepper et al., 2003). Kretschmer et al. (2008) point at integrating land-supply curves into the DART model, enabling assessment of indirect land use effects and emissions thereof, as one of the most urgent improvements of the model.[28]

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[28] A possible start for this extension is developed recently by Kiel University and the Dutch Environmental Assessment Agency (Ignaciuk et al, 2009). This so-called DART-PBL model includes modelling of land use as in the LEITAP model (see par. 4.2.1).

4.2.4 CEPII's Mirage model

The MIRAGE model is a recursive dynamic GE model with global coverage, developed by the French CEPII institute (Centre d'Etudes Prospectives et d'Informations Internationales). Following Van Tongeren's typology (see chapter 2), MIRAGE would appear as a second/third generation GE-model, with several advanced features: product differentiation on the demand side (Armington elasticities) ánd supply side (imperfect competition in connection with scale effects, different product-qualities and the like). The production-structure mirrors the basic structure of the standard GTAP model (see fig. 4.1): a Leontief function (with $\sigma=0$) of value-added and intermediate inputs; CES-functions describe substitutability within the value-added nest respectively the intermediate inputs nest. The structure of the value-added nest differs however, by distinguishing unskilled labor and a skilled labor-capital composite (besides land and natural resources). The demand side (households) is modelled through a representative agent with constant propensity to save, but with income-dependant consumption preferences (non-unitary income elasticities).
In its generic version, the MIRAGE model distinguishes 10-15 regions and 25-30 sectors. This original version has been used for medium term (a few decades) assessments of trade policy issues.

Early 2009, CEPII – in collaboration with IFPRI and other institutes – presented an assessment of EU-biofuel policies, based on an expanded version of MIRAGE (final report ATLASS consortium: Bouet et al, 2009). In this version several significant changes are incorporated in the model:

- the sector decomposition was revised, by introducing two biofuel producing sectors (bio-ethanol, biodiesel) and by separating their main feedstock crops and fertilizer from larger sectors. So was the geographic decomposition, by distinguishing main producers like Brazil, Indonesia an Malaysia. The revised model counts 18 regions/countries and 33 sectors.
- the 'nested' production structure was redesigned, following the approach of GTAP-E (see par. 4.1.2). 'Energy' was transferred from the intermediate inputs nest to the value-added nest (more precisely: 'capital' in MIRAGE's skilled labor-capital composite was replaced by a capital-energy composite), and specified in terms of energy sources. As in GTAP-E, this allows to model substitutability between energy sources and between energy use and capital (representing e.g. energy-efficiency investments). Moreover, also 'fertilizer use' was transferred to the value-added nest (of agricultural sectors), where it forms a composite with land use. In this way the choice of farmers between a relatively extensive or relatively intensive production process has been modelled. Bouet et al. note that the substitution elasticity between land and fertilizers is one of two key parameters on which reliable, worldscale information is missing. They adopt elasticity values (differentiated for regions and crops; adapted for application in a GE-model context) from IFPRI's IMPACT model (see par. 3.5), in their central case. A sensitivity analysis is added, which shows the effect of assuming higher elasticity values.
- A land use module was added, which models substitution between crops on existing arable land (cropland), as well as extension of arable land at the cost of pasture land, and/or managed forests, and/or natural forests or grasslands.
  This module builds on the GTAP-AEZ approach (see par. 4.1.3) to assess *substitution effects* within each region/country, differentiated for 18 agro-ecological zones (AEZ's); elasticities are taken from OECD's Policy Evaluation (PEM) model.
  Assessment of *extension effects* starts with combining land rent values (adapted GTAP data) and land use data – existing and potentially available land for rain-fed crops – in physical units (IIASA-FAO data). Next, the magnitude of cropland extension is determined, as a function of rising prices of land (triggered by increased biofuel demand and inelastic food demand) and the elasticity of cropland supply. Both are country specific. Bouet et al. (2009) point at this elasticity as the other key parameter on which consensual information is lacking, especially regarding developing countries. In their central scenario, they apply two elasticity values: 0,05 resp. 0,1 for countries with limited resp. extended land availability. A sensitivity analysis is added, which

shows the (substantial) implications if *for developing countries* a five times higher elasticity (0,25 or 0,5; depending on land availability) is assumed.
The assessment of land extension effects is completed by allocating additional cropland hectares amongst AEZ's, following historic patterns of land use change (in other words: future land use changes are assumed to take place in locations which underwent changes in the past); and by computing their productive (resp. rental) value. Here, Bouet et al. take advantage of the approach developed by Banse et al. (2008; see the LEITAP model; par. 4.2.1), but at the same time deviate from it, by applying *marginal* values instead of the average rental rate in LEITAP's land supply curve.

The expanded MIRAGE model has been applied to evaluate economic and environmental effects of two policy scenarios, namely achieving 5% biofuels consumption in transport fuels in 2010, rising to 10% in 2020; with or without continuation of actual import tariffs. The GTAP 7 database (with base year 2004) was used as social accounting matrix. The environmental evaluation focuses on CO_2 emissions, both direct and indirect (caused by land use change), with emission factors mainly based on IPPC and FAO data. The by-products of biofuel production are however not included in this evaluation, nor are second generation biofuels and emission of non-CO_2 greenhouse gases.

4.2.5 ABARE's Global Trade and Environment (GTEM) model

The global trade and environment model, in the late nineties developed by the Australian Bureau of Agricultural and Resource Economics (ABARE), is a recursive dynamic GE model, with global coverage. It was derived from a earlier GE model, designed by ABARE – the Megabare model –, and the standard (static) GTAP-model (Hertel, 1997) and inherits characteristics from both. The GTAP-database is used as its main, but not exclusive data source (Social Accounting Matrix). Additional data are required because of some special features of GTEM, most notably:

- the elaborate population module, which endogenously links demographic changes with economic growth and vice versa;
- the environmental module, which tracks anthropogenic emissions of the major greenhouse gases (e.g. CO_2, fluorine gases, nitrous oxide from transport) from combustion ánd non-combustion sources; main exemption are land use related emissions. This module also lodges emissions response functions, and provisions to model a number of policy measures which may provoke such responses (like taxes and emission trading systems of various shape);
- the 'technology bundle' approach, i.e. modelling of different technologies, available in certain energy intensive sectors (notably: electricity and iron/steel sectors); whereas GE models normally assume homogenous sector technology; this bottom up type of modelling enables evaluation of technological choices in these sectors, e.g. renewable technologies or CCS in electricity generation.

The GTEM model is continuously improved, and adjusted to specific applications. Its actual structure is documented by Pant (2007). An early application is the assessment of proposed European climate change policies, commissioned by the EU (Jotzo et al., 2000). The focus of this report is on least cost strategies to implement the Kyoto-protocol targets. This is analysed in a GTEM setting with 23 regions/countries and 19 sectors; using the GTAP4 database (adapted to GTEM). Biofuel production is not distinguished as a sector or otherwise analysed as a emission abatement strategy.
Recent applications include – among others – an assessment of a long term, low emissions scenario, based on a rapid uptake of advanced technologies and alternative energy sources (Gurney et al., 2007) and ex ante evaluation of Australia's emission trading scheme (CPRS: Carbon Pollution Reduction Scheme), which is to be introduced from 2010 onwards (Ford et al., 2009; Lawson et al.,

2008, Burns et al. 2009). Gurney et al. use the (for GTEM adapted) GTAP6 database, with aggregated data for 18 regions and 28 sectors; biofuel production being one of them. In their study biomass-based energy plays a significant role, both as a feedstock for electricity generation, and as (second generation) biofuel for transport. Biomass is expected to become the most important renewable (non-hydro) energy source in 2050, globally as well as in Australia, and to contribute significantly to emission abatement in these sectors. However, Gurney et al. underline that land use change and related emissions are not evaluated.
Ford et al. (2009) assess CPRS impacts on agriculture, but bioenergy production from agricultural feedstock is not distinguished. Lawson et al. (2008) and Burns et al. (2009) analyse impacts on forestry (including land use change from agriculture to forestry), but they only assess prospects for forestry as a carbon sequestration strategy. Bioenergy perspectives are not evaluated here either.

All in all it appears that "one of the important features that are missing in GTEM so far is the land use change modelling", to quote Pant (2007), GTEM's main modeller. His observation that "addition of some mechanisms in GTEM that captures optimal changes in land use and its net contribution to GHG emissions would certainly enhance the usefulness of the model" is still relevant today.

4.2.6 Other GTAP related models

There are a number of other users of the GTAP model and/or the GTAP database, often modifying it towards own needs or linking it to other models. A non-exhaustive list includes the following:

- The FARM (Future Agricultural Resources) Model, developed by Darwin in the mid-nineties, is an extended version of the standard GTAP model. Darwin pioneered the inclusion of land and water as scarce and spatially decomposed resources. Their supply is modelled on the basis of rules, not on behavioural equations (Darwin et al, 1995).
- The GRACE model is developed by Cicero (Norway), as a dynamic GTAP-version, especially focussing on forestry (Aaheim, 2005, 2006).
- The KLUM/GTAP modelling system is a linkage between the KLUM model, developed by Hamburg University to analyse global agricultural land use, and the standard GTAP model (with a prolonged time horizon to 2050) (Ronneberger et al., 2005, 2009).

5. Bioenergy analyses using non-economic models

5.1. De-/afforestation: IIASA's G4M and DIMA models

5.1.1 General features

The global forestry model (G4M), developed by the International Institute of Applied Systems Analysis – Ilasa (forestry program), is designed to predict agents' decision making on converting forests into agricultural land (deforestation), to avert from such land use changes in case of policies which value carbon sequestration ('avoided deforestation'), or – vice versa – to convert agricultural area into forest (afforestation). G4M (Gusti et al., 2008) is the successor of IIASA's Dynamic Integrated Model of Forestry and Alternative Land Use (DIMA) model (Kindermann et al., 2006; 2008), which was largely confined to deforestation and avoided deforestation.

G4M (and DIMA) suppose that agents – e.g. landowners – are economically driven: their incentive is to maximize net present value of their land. Nevertheless, G4M is regarded here as a non-economic model, because it does not contain a market clearing mechanism: feedback loops, balancing (land-) quantities and prices, are absent in these models (but see par. 5.1.3).

G4M (and DIMA) assess land use dynamics at 0,5° x 0,5° grid cell level across the globe, building on detailed biophysical datasets from FAO and other sources, and predicting forest shares for every grid cell during several decades ahead. Besides grid cell data, the model equations contain several factors and parameters which are determined at country level – i.e. national land price levels and national policies delimiting deforestation rates – or at the still more aggregated level of 11 world regions – i.e. land and wood price indices.

Assessment follows two steps. First, net present values (NPV) of forestry and agriculture are calculated for each grid cell, including corrections for carbon emission/sequestration if relevant. Second, if NPV-forestry appears lower (higher) than NPV-agriculture (plus benefits from selling wood after clear cutting a forest), and if some additional conditions are fulfilled, the model concludes that deforestation (afforestation) will occur; than the model proceeds by calculating a *rate* of deforestation/afforestation (which may continue till the forest share in a grid cell's total land area approaches 0 respectively 100%).

A few details may enlighten this basic approach:

- forests are assumed to be (more or less) actively managed; their net present value depends on rotation length, planting costs, harvestable wood volume, wood price and eventually C-sequestration benefits; if relevant multiple rotation periods are included (depends on simulation horizon an type of forest/plantation). Future values are discounted according to a country specific, 'risk-adjusted' discount rate.[29] In the DIMA model, wood prices may fluctuate within the price range in a reference country (Brazil; e.g. 5 – 35 $/m^3, expressed in 2000 USD), depending on population density and forest share in grid cells: relatively high wood prices are expected when population density is high, forest share low; and vice versa.
- The price of agricultural land is assumed to reflect its net present value. In the DIMA model this price can fluctuate between 200 and 900 $/ha (in 2000 USD; these maximum and minimum values again are taken from Brazil as the reference country), depending on agricultural suitability and population density in each grid cell. Higher suitability/density enforce the agricultural land price to approach the maximum, according to a Cobb-Douglas function.

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[29] In short: high in developing countries, relatively low in rich countries. Obviously, the higher discount rates are, the sooner future values loose their relevance (weight) in calculating NPV.

- In G4M the limited price flexibility of wood and agricultural land has been broken, by introducing a factor into both price equations which reflect exogenous price corrections (i.e. generated through interaction with other models; see par. 5.1.3).
- Decisions on deforestation/afforestation basically rely on comparing net present values, including revenues from clear cutting forest and – eventually – corrections for C-sequestration and/or emissions (see above). Additional conditions are that land use change is not prohibited, e.g. excluding areas which status as forest or agricultural land is secured. Moreover, the NPV of forest areas is multiplied by a country specific[30] 'hurdle coefficient', reflecting effects from national policies to discourage deforestation/encourage afforestation (if such policies exist).
- Deforestation/afforestation *rates* are calculated at grid cell level, assuming maximum rates (relative to total grid area) of 5%/yr deforestation, respectively 1%/yr afforestation (only in G4M).[31] Prospected rates deviate from these maximums according to a non-linear function, including (exponential) factors which reflect initial forest share, agricultural suitability, population density and GDP (in case of afforestation only agricultural suitability and GDP appear relevant), in accordance with results of regression analysis.

5.1.2 Treatment of land use and GHG-balance impacts

The focus of both IIASA models is clearly on land use change, whatever its causes. Main drivers are factors like population density, agricultural suitability, wood prices and agricultural land prices. So, the DIMA and G4M models, in their stand alone mode, are not fitted to assess land use impacts from a specific cause, like increasing bioenergy production.

Both models do enable assessment of GHG-impacts from land use change; DIMA in a limited sense, namely restricted to the loss of above ground biomass in case of deforestation (carbon emission by releasing stored carbon); respectively preventing such emissions in case of avoided deforestation. This implies that also the impact of carbon prices, applied in agriculture/forestry sectors, and/or payments for accumulation of carbon can be evaluated. Such prices/payments are modelled as a new factor in the equations, which represent decision making by landowners. Also added is a correction factor, which accounts for leakage effects, depending on governance related factors like corruption and political stability. The G4M model follows this approach, but with an improved carbon accounting module: below ground carbon, soil organic carbon and litter/woody debris are now included.

5.1.3 Interaction with other models

The G4M model was explicitly designed for combined application with IIASA's GLOBIOM model (see par. 3.6). When both models are coupled, GLOBIOM delivers endogenous wood- and agricultural land prices, at regional specific level (11 world regions). These prices enter the NPV-equations (forestry and agriculture) of G4M, and so function as exogenous drivers for the geographically explicit G4M results. In fact, G4M becomes the land use module of GLOBIOM, providing for a sophisticated downscaling algorithm for GLOBIOM results.[32] In GLOBIOM bioenergy developments may drive price changes. So, the combined use of this model and G4M enables to assess grid cell specific impacts from bioenergy on land use and related carbon emissions/sequestration.

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[30] The DIMA model applies a global hurdle factor, with value 1.5; G4M applies country specific hurdles, derived from calibrating the model to match 2000-2005 FAO-data.

[31] Moreover, in G4M, both maximum rates are tuned with country specific multipliers, in correspondence with calibration results.

[32] On its turn G4M/Globiom are part of a still broader 'global integrated modelling framework', designed by IIASA as a 'multi-model toolbox' to assess interactions between land use related mitigation measures.

5.2 Integrated assessment: PNNL's GCAM (MiniCAM) model

5.2.1 General features

The Mini-Climate Assessment Model (MiniCAM) was developed in the early eighties by the Joint Global Change Research Institute of the US-Pacific Northwest National Laboratory (PNNL). Its original version combined a partial equilibrium model of the global energy sector and a earth-climate model. Later on two new modules were added, covering agriculture and land use (again a partial equilibrium model), respectively regional climate change patterns. All modules can run separately, but in MiniCAM they are linked by means of iterative procedures.
In fact, the two climate modules were existing models, developed by the US-National Center for Atmospheric Research (NCAR). Both economic modules are developed at PNNL, as well as the interaction between the four. In order to improve this interaction and the consistency of the model as a whole, an integrated assessment modelling framework was developed, called ObjECTS: 'Object-oriented Energy, Climate and Technologies framework (Kim et al., 2006); recent versions of Minicam are implemented within this framework. Finally the name MiniCAM has been changed very recently into GCAM.
To prevent misunderstanding, we will indicate the model as MiniCAM/GCAM; our short description is based mainly on Brenkert et al. (2003) and Wise et al. (2009a, 2009b); other sources are Kim et al. (2006), Clarke et al. (2007).

From its start, MiniCAM/GCAM focuses on long term climate change impacts and policies. The model usually looks a century ahead (1990-2095), divided in 15-year intervals. This is done by evaluating long term scenario projections, based on various views on future economic and energy use/supply developments (so called 'storylines'). The model distinguishes between 14 world regions, 7 of which correspond to the Annex I countries of the Framework Convention on Climate Change (FCCC); the other 7 to the Non-Annex I countries.

As noticed above, the climate modules of MiniCAM/GCAM are filled up with two existing models, developed by NCAR. They are named MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) and SCENGEN (SCENario GENerator).
MAGICC is a relatively simple (according to IPPC definitions) climate model, which simulates (in annual intervals) the causal chain from emissions to atmospheric concentrations, to radiative forcing, to global-mean climate change, ice melting and sea-level rise. In MiniCAM/GCAM, data inputs for MAGICC (e.g. GHG-emissions, other emissions) come from the economic modules. MAGICC-outputs (i.e. global mean temperature) go to the SCENGEN module, which in his turn simulates regional patterns of temperature-, precipitation- and wind speed change, at a $5^0 \times 5^0$ grid level. The SCENGEN results can be used as feedback input into the agriculture/land use module, determining the 'climate factor' in yield equations (see Brenkert et al. (2003); the way how this is done, including aggregation from $5^0 \times 5^0$ grid cells to regional level, is not specified however).

The energy supply and demand module of MiniCAM/GCAM distinguishes four primary energy markets[33]: conventional/unconventional oil, coal, natural gas and biomass (from waste or dedicated production). Their supply equations include assumptions on resource constraints, like regional availability and global exhaustion, making abundant, easily obtained resources cheaper than more

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[33] Renewable sources like solar and wind energy are not included here, as they are not traded. They enter the model through their technologies; see below. Uranium is traded, but not in an explicit market; therefore it is represented by a cost equation.

limited, higher grade resources. Reflecting MiniCAM/GCAM's long term focus, a wide range of conversion technologies is specified, either currently applied or in some future expected (ranging from fuel cells to second generation biofuels, biomass gasification and space solar PV); as are new energy carriers (like synthetic fuels, hydrogen) and accompanying technologies (like carbon sequestration). Associated conversion losses are accounted for. For each technology a supply equation is specified, usually as a Leontief equation with constant input-output coefficients and including technical change parameters (exogenously determined at each 15-year time step). Competition between energy sources/technologies is simulated by 'logit share' equations; a methodology which pictures impacts from competition as smoothly changing *shares* of different sources/technologies in supplying energy demand.

Energy demand is specified for each region and energy carrier, distinguishing three end use sectors: buildings, industry and transportation. Demand equations comprise exogenously determined factors (population, GDP), assuming constant price and income elasticities, and a technology factor, reflecting (end use) energy efficiency assumptions.

Supply and demand firstly interact at regional level, including effects from regional taxes and tariffs, balancing demand for end use energy carriers and their supply, in an iterative process with primary energy sources' supply. Regional markets interact with global supply and demand, again in an iterative process and implicitly assuming trade (implicitly, because trade volumes from one region to another are not defined; total trade volumes from/to a region are). The whole process results in globally balanced supply and demand for each primary fuel: equilibrium (endogenous!) prices and quantities at each 15 year time step).

A distinct feature of MiniCAM/GCAM's energy module is the existence of a GHG-market (in terms of carbon or carbon equivalents), next to the primary energy markets. This feature enables to model climate policies, by assuming either a global carbon price (tax) or a global emission constraint (cap) for each time period. Alternatively, regional carbon taxes or caps may be assumed, resulting in independent regional markets. Clearing this/these market(s) proceeds simultaneously with the balancing process of primary energy markets.

Finally, the energy supply and demand module also calculates GHG (and a few other, like SO_2) emissions from energy producing and -transforming activities (and from some industrial processes like cement production and waste management).[34] This includes feedback effects, resulting from the GHG-market. These output data are then (combined with agriculture/land use emissions, calculated in MiniCAM/GCAM's fourth module; see below) applied as input in the climate modules (see above).

Biomass from purpose-grown energy crops is the main linkage between the energy supply and demand module (where its price is endogenously determined) and the fourth module of MiniCAM/GCAM, covering agriculture/land use.

This so called AgLu module distinguishes 7 aggregate land-based products: four composite crops, 'pasture products' (i.e. animal products), and two forestry products - currently harvested wood respectively 'future wood' (i.e. recently planted trees[35]). These composite land-based products meet demand on different markets: global markets, including interregional trade, for crops and processed crops; regional markets for animal products (interregional trade in animal products is considered negligible); global markets for industrial wood and fuel wood.

Fuel wood appears as one of two bioenergy feedstock chains in this module. The other is dedicated production of short rotation (cellulosic) energy crops, like switch grass and willow. Demand for energy crops is determined in the energy sector module, where this type of biomass competes with

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[34] Bioenergy is treated as carbon neutral, but biomass related land use change is not; see below.

[35] Forestry refers to commercially managed forests, assuming 45 year rotation periods; i.e. spanning three MiniCAM/GCAM time steps.

(usually cheaper) biomass from waste. In other words, in MiniCAM/GCAM, dedicated energy farming prospers only when biomass from waste falls short, e.g. in scenarios with high prices of fossil fuels and/or carbon.

The focus of AgLU module is on land allocation and related GHG emissions. It distinguishes five alternative land uses (see fig. 5.1)[36]; crops and purpose-grown biomass are grouped in a nest, because it is assumed that land for growing crops competes directly with land for growing energy-crops like switch grass and willow. During any model time-step, some land is already committed to trees previously planted (forestry). Other land will be allocated among crops/biomass, pasture, newly planted trees and unmanaged land.

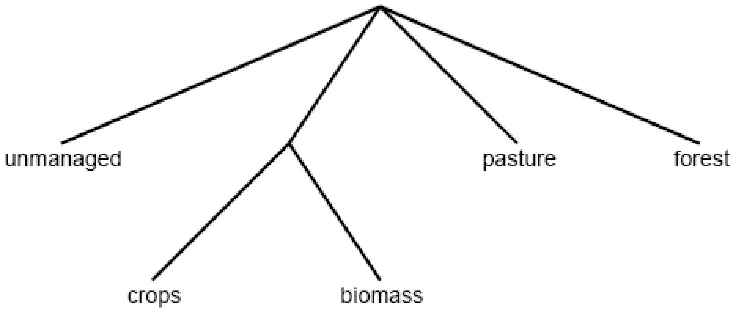

Fig.5.1 Nested land use categories in MiniCAM/GCAM

The model assumes that this allocation process is based on profit maximizing behaviour at each location within regions, i.e. revenue per hectare less (non-land) production costs are maximized. 'Locations' are defined in an abstract way: it is acknowledged that they differ regarding their suitability for growing crops, trees, pasture etc., but the AgLU module does not rely on geographically explicit data on location suitability. Instead, the model assumes a probability distribution of land suitability, which determines divergent 'intrinsic yields' of each region/land use combination. Given this assumption, profit maximizing regional land shares can be calculated, starting by using the most productive lands for the most profitable product categories, and expanding into less suitable lands. In a second step, this calculated, 'intrinsically' optimal allocation is calibrated, according to regional land shares in the base year.

AgLU also calculates GHG-emissions (and carbon sequestration) from land use and land use change. Each land use category is assigned a carbon density for soils and above ground plant material (carbon stocks/ha). Changes in land use are translated directly to changes in carbon stocks; the equations for soil carbon include a parameter reflecting decay rates.

In addition, non-CO_2 emissions are evaluated, especially methane and N_2O from agricultural and forestry practices like rice cultivation, fertilizer use, enteric fermentation and forest burning.

5.2.2 Treatment of land use and GHG-balance impacts

Given its general features, we may conclude that MiniCAM/GCAM is able to assess long term shifts in land allocation and its climate impacts in an integrated way. Carbon stocks and fluxes (including emissions ánd sequestration) are covered. Spatially explicit, sub-regional data and prognoses are absent however.

Wise et al. (2009) present an example of MiniCAM/GCAM's capabilities, by comparing global scenario's for atmospheric carbon mitigation with or without inclusion of terrestrial carbon

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[36] In Minicam/GCAM applications these five basic land uses may be differentiated. E.g. in Wise et al. (2009) there are five types unmanaged land: rock/ice/desert; tundra; shrubland; unmanaged forest; unmanaged pasture. Also other land use categories may be subdivided.

emissions. Essentially, Wise et al. assume a common carbon tax on fossil fuel-, industrial ánd terrestrial emissions/sequestration; resp. only on fossil fuel- and industrial emissions. They optimize tax levels to reach the same policy goal (450 – 550 ppm atmospheric CO_2 in 2100).
Wise et al. find radical differences between both scenarios, looking at efficiency (taxes rates need to be considerably higher when terrestrial emissions are exempted); at bioenergy growth (very expanding if terrestrial emissions are exempted; rather limited if not); and at land use allocation: managed and especially unmanaged forest increase their share when terrestrial carbon is valued (taxed). In the opposite case – only fuel related and industrial emissions are taxed –, bioenergy crops outcompete virtually all land uses except for food and fibre (wood) demand.
Wise et al. also demonstrate the relevance of (exogenously assumed) crop productivity growth. Zero productivity growth implies that more land is needed for food production. This strengthens the pressure for deforestation, releasing to carbon stored in vegetation and soil.

5.3 Integrated assessment: PBL's IMAGE model

5.3.1 General features

The IMAGE (Integrated Model to Assess the Global Environment) model was developed in the late 1980s by the Dutch Environmental Assessment Agency (PBL in Dutch; formerly known as MNP, and still earlier as RIVM). Its first version was a global, single-region model, focussing on climate change and its impacts at the global level; soon after this global focus was shifted to a partly regional (economic drivers and impacts) and partly grid-based (e.g. land use, population, biophysical impacts) approach. Parallel to this shift, IMAGE was developed towards capturing more domains of sustainability, ranging from ecological issues (like biodiversity, water depletion, land degradation) to equity issues (e.g. the fairness of global emission mitigation policies). IMAGE is used for long term assessments, usually up to the year 2050 or 2100.

From its first version, IMAGE was designed as a flexible *framework* embracing a number of modules, several of which were originally developed as separate models by PBL or elsewhere. In the course of time modules have been improved or exchanged for more sophisticated ones, while also – in the context of certain applications – certain modules may be switched off or replaced by external sources (either data or model outputs).
In the current version, IMAGE 2.4 (Bouwman et al., 2006), modules/external models are grouped in four main clusters: the socio-economic system, the earth system, (ecological) impacts and (climate) policy options. Modules/external models can be coupled in several ways, either by one-sided or two-sided (iterative) procedures. Most of them are applied at the aggregation level of 24 world regions and/or 0,5^{0} x 0,5^{0} grid cells (some modules deviate, by distinguishing 17-28 regions).
We will discuss only the most relevant IMAGE components and their coupling, with a view to bioenergy analysis.

The *socio-economic system* contains four components: demography, world economy, energy system, and agricultural economy and trade. Population and world economy are seen as the key drivers of economic/environmental change.
Population projections are either taken from external sources (delivering exogenously determined input for the energy supply and demand module), or are delivered by the demographic model Phoenix, included as a module within the IMAGE framework. This Phoenix module allows for feedback from other IMAGE modules – economic and environmental effects on fertility, mortality and migration rates – and produces output at regional (28 world regions), national or 0,5^{0} x 0,5^{0} grid cell level.
Macro-economic projections are taken from external sources (e.g. the Worldscan model), applied in combination with IMAGE. This reflects the absence of a (PE or GE) model of the world economy within the IMAGE framework; a shortcoming which hinders analysis of feedbacks from other IMAGE modules on the economy.

Energy supply and demand are assessed by TIMER, one of the main modules within the IMAGE framework. TIMER is a simulation model, describing demand and supply of 12 primary and end-use energy carriers for 17 world regions (recently also a 26 region version was developed). It predicts energy supply responses to developments in energy demand (as a result of changes in population and economic activity). These responses are assessed at regional level, including interregional trade.
As a simulation model, TIMER's results depend on deterministic algorithms, not on (economic) optimization in a market clearance setting. More precisely, the algorithms do take account of factors like primary energy prices, costs of energy production and conversion, technological

improvements in energy production and conversion, sector change (all exogenously determined), and end-use efficiency. But feedback loops balancing energy supply and demand (quantities and prices) are not modelled, except one feedback mechanism representing price induced energy efficiency improvement.
Finally, TIMER includes a emissions sub-model which calculates regional atmospheric emissions (GHG and other gases) from energy and industry-related processes, using time-dependent emission coefficients (reflecting technological improvements, future control techniques etc). Calculated emissions are input to IMAGE's earth system.

Modern and traditional biomass are two of the primary energy sources, distinguished in TIMER; modern biomass can be converted into bio-solid or bio-liquid fuels, used in industry and power sector resp. in transport. Biomass supply (specifically sugarcane, maize, short rotation wood and residues) and demand (from end use sectors) are assessed in a sub-model of TIMER. This sub-model applies economic optimization, contrary to elsewhere in TIMER.
The TIMER model/module, including this biomass sub-model, has been applied to assess biofuel scenarios and their land use impacts, but in a restricted sense only: producing energy crops was restricted to abandoned agricultural land and natural grasslands in such simulations, effectively avoiding competition with other crops. Because of this restriction we will not further investigate these applications.

Agricultural economy and trade prospects – the fourth component in IMAGE's socio-economic cluster – are also taken from an external source. In recent IMAGE applications the LEITAP model (see par. 4.2.1) is frequently used as such. Here, the TIMER module is switched off; the demand for bioenergy feedstock is modelled within LEITAP itself, based on exogenously determined energy prices and supposed policy measures. Bioenergy feedstock supply, i.e. production of bioenergy crops, is analysed as competing with traditional agricultural products – competing for land and other production factors. Land use change is assessed, employing an (iterative) linkage between LEITAP and IMAGE's earth system cluster (see below).

IMAGE's *earth system* comprises a number of biophysical models, referring to terrestrial subsystems (managed land and natural habitats) as well as atmosphere-ocean systems (not discussed here) and their interrelations (e.g. through carbon, nutrient and water cycles). A distinctive achievement of IMAGE is the grid-based disaggregation level ($0,5^0 \times 0,5^0$ grid cells) of most earth system modules, e.g. depicting actual and historic land use (distinguishing 14 natural and five anthropogenic land-cover types, next to urban area), as well as land suitability for agricultural uses (based on climate and soil conditions).

Besides land use assessment, in interaction with LEITAP, the earth system modules cover a number of other dynamic features, e.g. impacts from (changing) land use on the terrestrial carbon cycle, carbon sequestration in natural vegetation and 'carbon plantations', and impacts from diverging (pastoral vs. mixed/landless) livestock production systems on methane emissions, nitrogen cycles etc. The earth system modules of IMAGE also take feed back mechanisms into account, e.g. climate change impacts on land productivity.
One example to illustrate the detailed level of modelling earth system dynamics: if natural vegetation re-grows after abandonment of pasture or cropland, the net primary production is expected to increase to its maximum value after specified transition periods (ranging from 2 years for grasslands to 20 years for boreal forests). Reaching the equilibrium biomass (above ground and soil carbon stocks), however, will take much longer according to the earth system modules.

IMAGE's earth system modules are not described in detail here. The same goes for the third and fourth cluster of IMAGE modules: *ecological impact modules* (e.g. on biodiversity; water- and air pollution; land degradation) and *policy option modules.* This fourth cluster – in which the *FAIR model* is the main constituent – enables to simulate environmental impacts and (distribution of) abatement costs of various international policy regimes, i.e. regionally differentiated targets/commitments regarding long term climate policies. The FAIR model distinguishes 17 world regions.

5.3.2 Treatment of land use and GHG-balance impacts

We will describe the iterative linkage between LEITAP and IMAGE's earth system in some detail. Firstly, building on its grid level climate and soil data and a crop growth model, IMAGE's earth system calculates the potential land productivity for each grid cell; then all grid cells in a region are ordered from high to low productivity, in order to obtain a land productivity curve for that region (measured in Mgr/km^2, or transformed to a relative scale). In IMAGE, land supply curves are estimated for (all) 24 world regions, derived from a basket of seven temperate and tropical, rainfed food crops.

Secondly, according to Tabeau et al. (2006), the (biophysical) land productivity curves are transformed into (economic) land supply curves, which relate agricultural land supply to the price of land (average rental rate). Assumptions are that this average rental rate is inversely correlated with land productivity[37], and moreover that supply curves exactly mirror the inverse of land productivity curves. Given these assumptions, regional land supply equations are estimated, including price (?[38]) elasticities and other parameters, which (inversely) reflect the shape of productivity curves. Grid cells with zero productivity (ice, desert) as well as urban area and protected bio-reserves are excluded from this procedure.

Thirdly, the iteration starts by implementing the land supply curves within LEITAP, where they foster the so called 'acreage response' of landowners on changing demand for agricultural products (expanding agricultural land in case of e.g. increased bioenergy demand; idling land in case of falling demand). Within LEITAP, this acreage response and the so called 'yield response' – the alternative strategy land owners may follow: land use intensification/extensification – are substitutable. LEITAP optimises both strategies, including interregional trade effects; the resulting expansion/shrinkage of agricultural land is fed back to IMAGE's earth system modules, where it is allocated – region by region and crop by crop – to grid cells according to certain allocation rules (besides land productivity, additional allocation rules are applied, e.g. regarding population density, proximity to water and roads and to existing agricultural areas). IMAGE's output – extent and allocation of agricultural land use – does not necessarily coincide with LEITAP's output, in the sense that the productivity of allocated land may diverge from what in LEITAP was expected (e.g. due to the additional allocation rules). An additional iteration is necessary in such cases.

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[37] Higher demand for agricultural products results in higher product prices, which make agricultural exploitation of less productive lands attractive and at the same time raise rents on all currently used agricultural lands; that is, higher product prices raise average rents. In this sense, higher average rents go hand in hand with expanding agricultural area.

[38] Strictly speaking, these regional supply equations do not relate land supply to a monetary unit, but to a 'land rental rate indicator', as Tabeau stipulates. How this indicator is calibrated, in order to reflect monetary rental rates in different regions, is not quite clear. Tabeau et al. (2006) only refer to a one-point calibration, by considering the initial rental rates (in IMAGE's base year) as equilibrium prices in de land market. Banse et al. (2008) shortly denote the same indicator as 'average land rental rate' (see fig. 4.4), but does not clarify the calibration method either.

From this description and from IMAGE’s general features, it appears that spatially explicit assessment of long term shifts in land allocation and related climate impacts is a main focal point of this modelling framework. Carbon stocks and fluxes (including emissions ánd sequestration) are covered. Image’s approach is based on very extensive sub-regional datasets, and a combination of economic, biophysical and system-dynamic (simulation) modelling practices. Mutually attuning IMAGE modules/external models, based on such divergent methodologies appears as a continuous challenge, as was illustrated by the transformation from biophysically defined productivity of land into economically defined land values.

6. Exploring bioenergy’s indirect impacts: concluding remarks

This report offers a brief survey of recent progress in modelling bioenergy growth and impacts. This survey is limited, both in extent and in depth. Its main focus is on economic modelling through partial equilibrium (PE) or general equilibrium (GE) models. Additionally a few non-economic models are included – a forestry model and two general assessment models.
Most extensively surveyed are the partial equilibrium models Aglink/Cosimo and FAPRI, and the general equilibrium GTAP model, given their prominent role in this field. A number of other models are discussed more briefly. Looking at the overall picture, it strikes that the PE models discussed here have different origins, while all GE models are descendants of GTAP (or are at least GTAP-related by using its data matrix).

Our overview shows a diverse and dynamic picture of modelling approaches. First, there are several models which focus on long time horizons (2100, or at least 2050); examples are the MIT-EPPA model, the two general assessment models MiniCAM/GCAM and IMAGE, and the IIASA models (G4M in connection with GLOBIOM). Such a long term focus inevitably implies uncertain assumptions, e.g. by anticipating the breakthrough of not yet practiced bioenergy technologies. Nevertheless, such simulations including novel technologies are of great value, because they scout possible long term bioenergy applications and impacts. Investigation of long term perspectives with current technologies only, is not very enlightening.
Most models, however, confine themselves to short to mid term time horizons (a few decennia), while staying on the firm ground of proven technologies; that is, first generation biofuels. To some extent such technological conservatism is unavoidable, as calibration and validation of economic models is based on historic data. But one has to realize that this may misjudge the future of innovative sectors like bioenergy.

A second common property of most models reviewed here, except EPPA and MiniCAM/GCAM, is that world energy (oil) prices are fixed exogenously, and indeed almost ever at levels which condemn bioenergy to policy driven growth. This mirrors the actual, but not necessarily a future state of affairs in most countries.

One of the issues on which especially GE-models show progress, is the distinction and careful analysis of two possible implications of growing biofuel production: intensification of agricultural practices and/or extension of agricultural acreage. These are denoted as the intensive margin or the yield response, respectively the extensive margin or the acreage response, both having very different environmental (and social) impacts. See e.g. the newest GTAP model versions, LEITAP and MIRAGE.
PE-models and non-economic models, except in linked application with GE-models, are less useful here, because they lack production functions representing behavioural choices by farmers with regard to primary factor inputs.

Next to this is the – perhaps most lively debated – issue of how to model extension of agricultural land. Different approaches exist; among them (1) modelling forestry land use by own (behavioural) supply and demand functions, competing with agricultural land use (e.g. in the G4M and MiniCAM/GCAM models); and (2) representing non-agricultural land supply by a biophysically based proxy (e.g. in LEITAP and IMAGE). Calibration/validation proves difficult for both approaches, in developed regions and most certainly in less developed regions.

Much effort is currently devoted to spatial disaggregation of land use data and environmental impact data. The aim is (1) to capture the heterogeneity of land as a primary production factor, and (2) to down-scale the outcomes of model simulations. In the meantime, 'agricultural ecological zones' (AEZ's) became a proven concept to reach the first aim; sometimes AEZ's are rather extremely disaggregated (e.g. according to $0{,}5^{0}$ x $0{,}5^{0}$ grid cells). This however complicates calibration/validation. A way out in such cases (e.g. applied in IMAGE), is to derive land allocation at grid cell level nót on economic optimisation but on allocation rules.
Some models (notably the CAPRI model) allow to disaggregate simulation results even further, e.g. till 1x1 km grid level, by applying post-model calculations. This may be attractive in view of interferences with local biophysical circumstances and of investigating social impacts. But it seems questionable from economic modelling perspective, as simulations represent *mean* expected behavioural responses, which on its turn supposes a sufficient number of actors, in this case farmers, in each spatial unit.
PE-model simulations are able to add much sectoral and spatial detail, compared with GE-model simulations; e.g. on supply of and demand for by-products from biofuel production, including its (direct) environmental impacts. However, in stand alone mode, PE-models are less suited to analyse indirect effects, because missing factor markets (for labour, capital, land) precludes sound economic analysis of such effects.

Finally, it is clear that several models are improved (or going to be improved), regarding their capacity to assess climate impacts from bioenergy production. Often, a broader perspective is chosen, including GHG emissions from agriculture as a whole and eventually carbon sequestration by forestry and agricultural practices. In several cases (e.g. FAPRI, GTAP-BIO, MiniCAM/GCAM, IMAGE) such assessments include estimated GHG-effects from land conversion.
One application was found in which the calculated GHG-impact from land conversion serves as a sustainability criterium of publicly promoted biofuels (California´s Low Carbon Fuel Standard Program).
Biodiversity impacts are not assessed by the models surveyed here, the CAPRI, SAPIM and IMAGE models being the only exception.

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