Cross sector land use modelling framework

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Abstract

The purpose of the model component in SENSOR is to quantify the effects of a comprehensive set of policies on land use. The need to include interaction between sectors as well as a high level of detail for each sector calls for a combination of *sector specific* and *sector wide* models. This chapter describes the modelling system, with emphasis on the linking of the models to a coherent system. Five sectors of significant importance for land use are modelled individually: Forestry, agriculture, urban land use, transport infrastructure and tourism. All models are connected as sub-modules to an economy-wide partial econometric model. In addition, a land cover model is used to disaggregate land use down to 1 km grid resolution.

The linking of such a diverse set of models in a consistent way poses conceptual as well as practical issues. The conceptual issues concern questions such as which items of the models to link, how to obtain a stable joint baseline scenario, and how to obtain a joint equilibrium solution for all models simultaneously in simulation. Practical issues concern the actual implementation of the conceptually sound linkages and provision of a workable technical solution. In SENSOR, great care has been taken to develop a sound linkage concept.

The linked system allows the user to introduce a shock in either of the models, and the set of results will provide a joint solution for all sectors modelled in SENSOR. In this manner, the models take a complex policy scenario as argument and compute a comprehensive set of variables in-

volving all five sectors on regional level, which in turn forms a basis for distilling out the impact on sustainability in the form of indicators. Without the extensive automation and technical linkages, it would not have been possible to obtain a joint equilibrium, or it would have required exorbitant amounts of working time.

Keywords

Model linking, sustainable land use, cross sector modelling, iterative recalibration

1 Introduction

A key characteristic of the SENSOR project is that it applies a *cross-sector* approach to land use. This approach acknowledges that different sectors of the economy interact via shared resources, of which land is of most interest in SENSOR. Although a cross-sector approach enables capturing important interactions between sectors – and thus analysing important topics – it brings the modeller to a classical dilemma: On the one hand, a model with great scope is desired in order to span across the sectors of interest; on the other hand, models spanning several sectors can pay less attention to the details of each sector.

Due to the trade-off between scope and detail, models tend to specialise in either one. In SENSOR, we attempt to resolve that dilemma by using a combination of models. For each of the five sectors of interest, one specialised sector model is *linked* to an aggregated cross-sectoral model. In that way, the advantages of detail in each sector model can be exploited, and at the same time the *interactions* between the sectors are captured by the aggregated model[1]. For example: The agricultural sector model in SENSOR is fairly detailed concerning agriculture, but omits all other land uses. In contrast, the macro model entails competition for land by all sectors. By a proper linking, the strength of the detailed agricultural model

[1] The reader may be familiar with EURURALIS and SCENAR2020; two projects with similar cross sector modelling ambitions. SENSOR differs from the EURURALIS project which uses only a cross sector model (Klijn, et al. 2005; MNP and WUR, 2007) and it adds to the SCENAR2020 study a better linking system and the inclusion of other sector models than agriculture (Nowicki, et al . 2006).

can be utilized without sacrificing the competition between sectors provided by the macro model.

The purpose of this chapter is to provide a description of the linked system of models used in SENSOR, with emphasis on *how the models work together*, in order to provide a consistent and comprehensive picture of the cross-sectoral land use modelling. First, we introduce the land balance concept used. Second, a brief description of each individual model is presented, sufficient for clarifying its role in SENSOR. The model descriptions contain references for further reading. Third, the linkages of the models are described in greater detail. Two final sections provide discussions and a summary.

2 Land balances

The modelling of *land use* is central to SENSOR. The total land area is divided into agriculture, forestry, urban (including tourism), transport infrastructure, and land unsuitable for or legally exempted from exploitation. The economic value of land depends strongly on its use, with reference to the broad classes mentioned above: The value of land for urban, tourism and transport use is higher than that for agriculture and much higher than that of forestry. Therefore we do not model a fully integrated market for land but work with the principle of hierarchical markets with inferior and superior land claims. Relative to agriculture, the claims for urban, tourism[2] and transport are superior and the claim from forestry is inferior. The land balance concept is illustrated in Figure 1.

The superior land claims together with land "unsuitable" for exploitation (i.e. areas with strong constraints in terms of soil quality and/or climate) and land under "nature protection" are not available for agriculture. Those land claims are symbolised by the shaded rectangles on the right hand side in the Figure, and they *limit* the total amount of land available for agriculture (asymptote L) in each country. Given the total amount of land available for agriculture, the supply of land for agriculture (supply schedule S, see also Meijl et al., 2006) depends on the land price in agriculture (λ, measured on the vertical axis). The price reflects the marginal cost of taking land into agricultural production. As indicated in the Figure, that curve approaches the "asymptote" L as the agricultural land price increases. Thus, the more land is used in agriculture, the higher the land price needs to be, as it becomes increasingly difficult to make additional

[2] The tourism sector has no own land use class, but is part of the urban land use.

land suitable for agriculture. The agricultural land demand (*D*) reflects the marginal productivity of land in agriculture. The amount of land use in agriculture (x) is determined by the price equilibrium, $S(\lambda) = D(\lambda)$. The amount of land ($L - x$) that is not used by agriculture is potentially available for forestry (or other climax vegetation)[3].

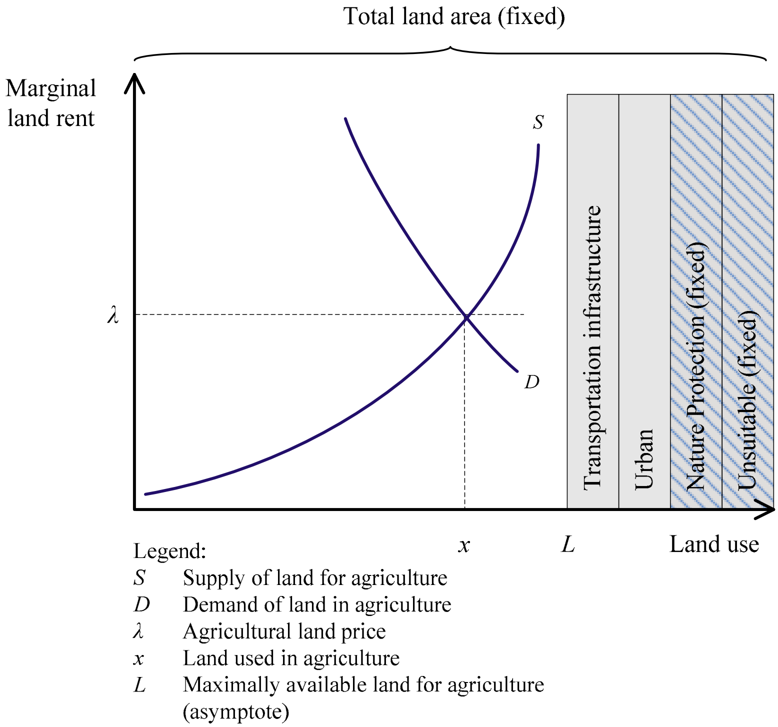

Fig. 1. Land balance in SENSOR. Land use for tourism is included in "urban".

The following example illustrates the mechanism: A "positive" shock to agriculture (e.g. increased food demand, increased subsidies, technical progress or rising commodity prices) works in three steps as described above (the steps are simultaneous; the order is intended to illustrate the economic hierarchy). Step 1: GDP, investments etc. change, and may influence the superior land claims "transportation infrastructure" and "urban". The asymptote L is shifted (small effect). Step 2: The demand schedule D is shifted to the right, determining a new agricultural land use x

[3] *Land potentially available for forest* is modelled on the level of land balances, but consists of different land cover classes. These classes represent different stages in the succession to forest and the *actual forest area* itself.

(the main effect). Step 3: The area potentially available for forestry, $L - x$, is reduced.

3 Overview of the models

In SENSOR we include a detailed macro-econometric model called NEMESIS, which models cross-sector impacts (see section 3.1). The sector models are CAPRI for agriculture, EFISCEN for forestry, SICK for urban, B&B for tourism and TIM for transport infrastructure (see sections 3.2 to 3.6). An important characteristic of NEMESIS is its land use module which includes three of the five sector models (SICK, TIM, and B&B models), as sub-modules. Using the SICK model, NEMESIS calculates land claims by housing as well as commercial and industrial building. Furthermore, NEMESIS derives the land claims for rail and road transport infrastructure from the TIM model, and uses the B&B model to compute the land used by tourism.

SENSOR also contains a land cover model called DYNA-CLUE. DYNA-CLUE disaggregates the land use on member state level computed in NEMESIS down to 1 km² grid units, and adds the land cover types: recently abandoned arable land, recently abandoned grassland, (semi)natural cover, forests and stable areas. It also distinguishes permanent crops from rotational crops. It then re-aggregates the land available for agriculture and forestry to sub-national regions for use in CAPRI and EFISCEN respectively. Before proceeding with a more thorough discussion of how the models are linked, we provide a brief overview of each model.

3.1 Macro- econometric model: NEMESIS

The economic model that makes the distribution of land claims between the sectors on national level is called NEMESIS (New Econometric Model for Evaluation by Sectoral Interdependency and Supply). It is a detailed macro-econometric model built for each country of the EU27 (plus Norway, USA and Japan) that uses as main data source EUROSTAT, and specific databases for external trade (OECD, New CRONOS), technology (OECD and EPO) and land use (CORINE 2000). NEMESIS is recursive dynamic with annual steps.

NEMESIS distinguishes 32 production sectors, including Agriculture, Forestry, Fisheries, Transportations (4), Energy (6), Intermediate Goods (5), Capital Goods (5), Final Consumption Goods (3), Private (5) and Public Services (1). Each sector is modelled with a representative firm that takes its production decisions given its expectations on marginal production capacity expansion and input prices. Firms' behaviour are based on new growth theories, where endogenous R&D decisions allow firms to modify the efficiency of the different inputs (biased technical change) and the quality of output (Hicks neutral technical change).

On the demand side, the representative household's aggregated consumption is indirectly affected by 27 different consumption sub-functions through their impact on relative prices and total income, to which demographic changes are added. Government (public) final consumption and its repartition between Education, Health, Defense and Other Expenditures, are also influenced by demographic changes. Please see Brécard et al. (2006) for a fuller description of NEMESIS.

3.2 Urban area: SICK

To be able to predict land use by urban areas, two types of enhancement to the NEMESIS model have been introduced. One principally relies on *bid-rent theory* for conversion of land into urban uses (Walker and Solecki, 2004). The direct effect of proxy-variables, such as GDP per capita and population growth upon urban expansion as measured in the CORINE datasets for 1990 and 2000 have been estimated (for a similar approach see Alig et al., 2004; Angel et al., 2005). The other type of enhancement uses a *Stock-flow approach* (DiPasquale and Wheaton, 1994; Mayer and Somerville, 2000) to model the supply of buildings, and combines this with a technical coefficient for land use of buildings estimated based on the urban land cover in the CORINE dataset for 2000. In this approach the urban land use is treated as a demand derived from the demand for housing (Muth, 1972) for which many of the relevant processes are already represented in the model. Its main basis is the net investment demand for buildings, which is modelled within the NEMESIS as part of the capital stock for each economic sector. Net investment demand for housing is added to the model as a function of real disposable income, real interest rates, and building prices. With the purpose of comparison and validation of the result both approaches to the prediction of future urban expansion have been employed.

3.3 Agriculture: CAPRI

The agricultural sector is the most important user of land in many regions, which motivates the use of an agricultural sector model to analyse the implication of policy scenarios in greater detail. The sector model used in

SENSOR is called CAPRI (see Britz 2005 and references therein for a full documentation). CAPRI offers a detailed depiction of the agricultural sector on regional level in the EU, with around 250 regions and around 50 agricultural primary and secondary products. CAPRI also contains a worldwide trade module, where 18 regional blocks trade bilaterally.

Agricultural production in European regions is determined by a mathematical programming model, which maximizes gross value added of a representative regional farm subject to technological constraints and a behavioural quadratic cost term. The quadratic cost term is derived from Positive Mathematical Programming (PMP, see Howitt, 1995), but the methodology has been improved in several respects: The problem of linear dependence between "calibration bounds" and model constraints, leading to unidentified dual values, has been alleviated by substitution of prior dual information for such model constraints in the calibrations step. In practice this means that regional grassland and arable land balances in the calibration step have been replaced by regional rental prices of grassland and arable land. Furthermore, prior information regarding the slope of the marginal cost curve (in the form of point supply elasticities) is exploited to resolve the indeterminacy of parameters in the "original" PMP method[4]. The behavioural cost term, thus specified, allows exact calibration of the model to one observed solution (as regards primal as well as dual variables, or decision variables as well as economic rents), and a first order approximation to supply *behaviour* in that point.

Demand is modelled on member state level and for about 40 regions in rest of the world using a Generalized Leontief expenditure system. The three sectors dairy, oil seed crushing and animal feed mixing, are modelled by profit function approaches. The European countries and the 40 world demand regions are aggregated into 18 trading blocks, each with its own set of agricultural trade policy instruments. Products of different geographical origin are distinguished on the demand side in a manner based on Armington (1969), similar to the specification in the GTAP model (Hertel 2004).

CAPRI contributes to SENSOR by implementing many policy instruments that are important determinants of regional land use, thanks to the model's detailed representation of the common agricultural policy (CAP) of the EU. CAPRI also serves to provide detailed results on agricultural land use on regional level, to provide NEMESIS with a land rent feedback and finally, via its technology representation, to provide inputs for the computation of environmental indicators in SENSOR.

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[4] Alternatives for the standard PMP approach are described in Heckelei and Britz (2005).

3.4 Forestry: EFISCEN

The forestry sector is the second largest user of land in Europe. Currently, 1-74% of the land area in European countries is covered by forest, with a European average coverage of 38% (FAO, 2006). Not only the extent of the forest *area* is important for sustainability, but more so the management practices employed on that area. The European Forest Information SCE-Nario model (EFISCEN) (Schelhaas et al., 2007) projects forest resource development on a given forest area and for a given demand for wood and management regime at European, national or regional scale (EEA, 2006; Karjalainen et al., 2003; Nabuurs et al., 2001; Schelhaas et al., 2006a).

The forest area is derived from national forest inventories along with the average growing stock and the annual increment. The forest area is divided into forest types that are defined by region, owner class, site class and/or tree species. The number of forest types differs per country and the detail level of the forest inventory data determines how many forest types can be distinguished. European wide data are gathered in the EFISCEN European Forest Resource Database (Schelhaas et al., 2006b).

In EFISCEN, the state of the forest is described in a matrix for each forest type separately, in which area is distributed over age and volume classes. Transition of area within the matrices represents different processes such as ageing, growth, mortality and harvest.

The transition of area can be influenced by wood demand, forest management and changes in forest area. Wood demand is in SENSOR projected by NEMESIS and is the main determinant of forest resource utilisation. If wood demand is high, management is intensive, and if wood demand is low, management is not intensive. Forest management regimes are based on a country-level compilation of management guidelines (Yrjölä, 2002). Forest area changes, resulting from aforestation and deforestation, are obtained from projections by DYNA-CLUE.

Based on the information mentioned above, EFISCEN projects stem wood volume, increment, age-class distribution, removals, forest area, natural mortality and dead wood for every five year time-step. With the help of biomass expansion factors, stem wood volume is converted into whole-tree biomass and subsequently to whole tree carbon stocks. Information on litterfall rates, felling residues and natural mortality is used as input into the soil module YASSO (Liski et al., 2005), which is dynamically linked to EFISCEN and delivers information on forest soil carbon stocks.

3.5 Tourism: B&B

The objective of the tourism modelling in SENSOR is to assess and predict the land requirement for tourism infrastructure developments per NUTS-X[5] region for the base year 2000 and for the year 2025. This requires, in the first place, a tourism demand model – linked to the overall NEMESIS – predicting tourism numbers. Secondly, to be able to distribute the flows of tourists from tourist generating regions to the tourist receiving regions, a bilateral tourism flow matrix is established and connected to the demand model. Thirdly, to distribute the flows at sub-national levels to the NUTS-X regions, tourism-attraction has been modelled and a tourism attraction index has been established. Finally, the immediate land use of tourism overnight facilities have been estimated and may hereby be separated from the urban land uses in which it is currently included. Eventually, the overall model should be able to predict how changes in demand is distributed at national and sub-national levels and compute the resulting spatial land use changes in tourism facilities. The tourism demand is modelled by an AIDS (Almost Ideal Demand System) following Deaton and Muellbauer (1980)[6].

3.6 Transport infrastructure: TIM

The main objective of the transport infrastructure model (TIM, see Ortiz 2005 and Ortiz 2006) is to predict the land requirement for new transport infrastructure developments in the EU27 given NEMESIS' projections of the demand for transport in 2025. NEMESIS' projections of the demand for transport are based on projections of key socio-economic indicators such as oil prices, GDP and population for the period of analysis, and are estimated from the households' and firms' total expenditures with transport. The total demand for transport in NEMESIS distinguishes total *passenger* demand for transport and total *freight* demand for transport, by transport mode: *road*, *rail* and *air* transport. The modelling approach for transportation infrastructure in SENSOR involves linking the demand for transport of households and firms first to road and rail extension and then

[5] All regions in SENSOR are official regions following the official nomenclature NUTS of Eurostat. Each member state is modelled either at NUTS-2 or NUTS-3 level, depending on what was deemed to be the appropriate resolution for that member state. The resulting total set of regions (the union over all member states) thus contains both NUTS-2 and NUTS-3 regions and is called NUTS-X.

[6] When this chapter was written, the tourism model was not yet fully developed and integrated into the modelling framework.

to land use, using conversion factors calibrated to data for France, Denmark and Belgium.

3.7 Spatial disaggregation of land use: DYNA-CLUE

NEMESIS provides future land use claims at the country level while some of the sector models work at NUTS-X level. In order to (i) bridge the gap between the outputs of NEMESIS and the input requirements of CAPRI and EFISCEN, and (ii) to provide more detailed land cover information for the computation of sustainability impact indicators, SENSOR uses a model named DYNA-CLUE. DYNA-CLUE disaggregates the land use claims to a one by one kilometer grid, and also allows the incorporation of spatial policies such as Natura2000 and the Less Favoured Area schemes.

DYNA-CLUE is a dynamic model with annual time steps, which distributes the land use on member state level given by NEMESIS to a 1 km resolution grid for 16 land cover types. The mechanisms of land use allocation included in the model can be divided in *location characteristic* and *conversion characteristic*. The location characteristic mechanism captures the suitability for each land use on each spot, and contains biophysical and socio-economic factors, and policy and neighbourhood effects (Verburg et al. 2004). Conversion characteristics are divided into conversion elasticities, determining the resistance of a land use type to change location, and transition sequences. A transition sequence is a set of rules that determine the possible land use conversions. Not all land use changes are possible and many land use conversions follow a certain sequence. For example, grassland cannot change into mature forest within a year. In the transition sequence it can be defined that grasslands first turn into regenerating forest after which it can change into mature forest after a certain time.

4 Principles of model linking

4.1 Upstream and downstream linkages

The models need to be linked in order to obtain a consistent simulation and to exploit the strengths of each model. This requires *upstream* as well as *downstream* linkages, because on the one hand, macro policies and interactions are only implemented in NEMESIS. Their effects must thus be communicated *downstream* to the sector models in order to capture the effects on the individual sectors. On the other hand, sector specific behaviours, for example impacts of the common agricultural policy, are only implemented in the sector models. In order to compute the effects of such policies on other sectors and the economy as a whole, the sector models must also communicate *upstream* to the macro level, where the effects can again be distributed to all sectors. The latter link is also required in order to obtain a consistent reaction of *all sectors simultaneously* to macro economic changes. Thus, bi-directional linkages are required. Böhringer and Rutherford (2006), linking a Computable General Equilibrium (CGE) model to a Partial Equilibrium (PE) model, termed this kind of bidirectional link “a combination of top-down and bottom-up”.

The *ultimate* link would be to *include* the sector models inside NEMESIS and solve them simultaneously. This solution has been chosen for the models SICK, TIM and B&B. Those models can thus be considered parts of NEMESIS, and are left out in the following exposition. The remaining models NEMESIS, CAPRI, DYNA-CLUE and EFISCEN cannot, for technical reasons, be integrated in one equation system. They are implemented in different software packages, in different forms (dual vs. primal[7]) and also require advanced numerical techniques to solve already as stand-alone applications. Instead of a simultaneous solution, an iterative recalibration solution for the linked system was opted for, similar to that which links the CAPRI supply and demand modules (Britz, ed. 2005) and also to that described by Grant, Hertel and Rutherford (2006). The remaining part of this chapter is devoted to the iterative linkage of models.

4.2 Considerations for the baseline calibration

Before discussing the linkages of the models, it is useful to consider the problem of generating a consistent baseline. A baseline is a simulation outcome that is used as a reference to evaluate other simulation outcomes (Kuhlman, 2008). In an ideal situation, the models would rely on identical drivers[8], contain equivalent assumptions and yield identical baseline forecasts for items that are common to the models. For example, the agricultural sector in NEMESIS would develop exactly as the aggregate agricultural sector in CAPRI. In practice, the models are so different, including different functional forms, starting data, spatial detail, and a multitude of assumptions and auxiliary data sources, that a fully consistent baseline pro-

[7] The dual approach gives a more indirect technology representation e.g. through an econometrically estimated cost function. The primal approach allows for a physical and explicit input-output technology description.
[8] By "drivers" we mean the exogenous factors which cause the model solutions to change from the base year (e.g. 2002 in the case of CAPRI) to the target year (2025)..

jection may not be possible to obtain. In fact, the different modelling assumptions are one of the main reasons for linking the models in the first place, and we would be quite surprised to find that the same results can be obtained in two conceptually different models. The baseline calibration problem is thus to devise a way of calibrating the linked system of models so that simulation of the baseline policy scenario also delivers a stable solution. That is, if the linked system is properly calibrated to a baseline, then the information communicated through any link is such that it causes the model on the other end of the link to produce precisely the baseline.

On the one extreme, the models could be forced to reproduce fully identical solutions. We call this[9] the *harmonization approach*. For reasons indicated above, full harmonization is not feasible in all cases. On the other extreme, the difference between the models could be accepted and interpreted as differences in definition of the underlying data and assumptions. In the latter case, the ratio between the linked items (here termed the *link ratio*) is computed in the baseline and maintained in simulations. We call this the *differential approach*. The differential approach is easy to implement, and can be used in combination with harmonization. It is, however, not desirable to choose the differential approach for all positions, since that would obscure true data problems and errors.

The chosen solution is a composite of both extremes, including both adjustments of the models to harmonize baselines and "freezing" of remaining differences. For NEMESIS, a baseline calibration program was developed that treats the agricultural production and prices as exogenous, given by the CAPRI baseline, and adjusts parameters of price, domestic demand, imports and exports equations so that the aggregated results of agricultural supply and demand coming from CAPRI are nearly perfectly recovered.

Several outputs of NEMESIS and DYNA-CLUE (see below) are exogenous in CAPRI. Nevertheless, it is difficult to use those outputs directly and fully harmonize the CAPRI database with NEMESIS and DYNA-CLUE: Firstly, CAPRI is an internally fully consistent system where it is difficult to change only one item, like one price or land availability, without influencing all other items in the model about which neither NEMESIS nor DYNA-CLUE provides any information. For example, changing the land use to reflect exactly the outcome of DYNA-CLUE would make the whole market balance of agricultural products in the baseline invalid. Secondly, adopting the outputs from NEMESIS and DYNA-CLUE straightaway, thus *changing* the CAPRI results, would be fed back to NEMESIS

[9] We are not familiar with any publication that treats the general problem of calibrating a linked system of models. The terms used here, i.e. “harmonization” and “differential”, were introduced to fill the gap.

(agricultural production and prices), thus *again* changing the inputs into CAPRI upon which the baseline was based. The hence-created circular flow may be difficult to break. Thirdly, there are also many cases where the level of aggregation is different, with CAPRI being more disaggregated than NEMESIS and DYNA-CLUE (in the sense of distinguishing more different land uses). Thus, for CAPRI, the differential approach for baseline calibration is opted for, which implies computing the link ratio between the pairs of linked variables in the baseline, and then using that ratio in simulations to translate a change in the foreign variable to a change in the linked CAPRI item.

For DYNA-CLUE, a similar differential approach is used. The land use statistics that NEMESIS uses (derived from EUROSTAT) do not always match the land cover data that serves as input to the DYNA-CLUE model (derived from CORINE). DYNA-CLUE therefore only takes the annual *changes* in land use areas from NEMESIS, and imposes these changes, corrected for an 8% land cover inefficiency factor due to infrastructure, parcel boundaries etc., to the land cover map. EFISCEN, finally, needs no special calibration procedure, since there is no overlap between the outcomes of EFISCEN and any of the other models.

4.3 Iterative solution of the linked models

The preceding section discussed some problems concerning how to obtain a calibrated baseline to which all subsequent simulations can be compared. In this section we treat the problems of devising proper linkages between the different models and finding a method for obtaining a joint solution to the whole linked system in any simulation. In principle, linkages between the models are established by for each model taking certain outputs (linked items) of the other models as given inputs. A solution is obtained by repeatedly solving the sequence of models, each time updating the linked items, until convergence is achieved. Issues as to whether a joint equilibrium exists and sufficient conditions for finding it in this way are beyond the scope of this chapter, where we focus on a description of the linkages.

The links need to be implemented in the macro model NEMESIS in a way that is qualitatively different compared to the specialised models DYNA-CLUE, CAPRI and EFISCEN. The latter models need only to take the values from NEMESIS as given, exogenous data, multiplied by the link ratio of the baseline. The upstream link, from a sector to a macro model, must be handled differently. Specifically, this is the case for the link from CAPRI into NEMESIS. In this case, NEMESIS already possesses an agricultural sector, which, in the context of SENSOR, is useful to consider an

approximation to CAPRI. The ultimate objective of the link is to adjust the agricultural equations of NEMESIS in such a way that they make a perfect approximation to the aggregate behaviour of CAPRI in a small area around the equilibrium solution. In SENSOR we are satisfied with a *point approximation*, i.e. to shift the functions in NEMESIS so that they run through the *point* which would result if CAPRI could have been fully included in NEMESIS (but ignoring the slope of the functions in that point).
The authors are aware of only few formal treatments in the literature of the problem of linking models. Grant, Hertel and Rutherford (2006), Böhringer and Rutherford (2006) and Rausch and Rutherford (2007) note that the linked system generally is a mixed complementarity problem (MCP), and implement what may be called Newton-Josephy-like iterative recalibration methods to solve it. This is also, in a wider sense, the approach used in SENSOR. A principal difference to e.g. Böhringer and Rutherford, who link a Computable General Equilibrium (CGE) model to a Partial Equilibrium (PE) model, is that where they remove the relevant equations from the CGE and replace them by first order approximations of the PE (i.e. linear functions that not only go through the same point as, but also have the same slope as the PE model), we keep the original equations in place and instead re-compute their parameters to obtain a point approximation. The advantage of the first order approximation would be faster convergence, whereas our approach requires less modifications of existing model code and ultimately leads to the same solution.
Under some circumstances, the iterating system will not converge. That may happen, for example, if a linked demand schedule is close to vertical and/or the slope of the corresponding supply function very big, and/or the initial shock is extreme (implying a solution out of technical bounds). In such cases, some other/additional mechanism is required in order to find the equilibrium. One such mechanism is to work with partial adjustments[10]. If partial adjustment is implemented in the sector model for, say, a price p that comes from upstream, then we use the weighted average price

$$p^i = \sum_{j=1}^{i-1} a_j p^{i-j} \qquad (1)$$

[10] Partial adjustments in the sense that only a fraction of the current solution of the macro model is going into the new parameters of the partial model. Alternatively, this could be expressed as a "lagged expectation" in the partial model, though that term is loaded with too much economic content and suggests a misleading interpretation of iterations as "time".

where a_j are weights that sum to one and indices (i,j) are iterations. For example, choosing $a_1 = 0.5$, $a_2 = 0.5$ and $a_j = 0$ for all $j \neq 1$ or 2, implies taking the simple average of the last two iterations.

Both convergence methods – the iterative approximations and the partial adjustments – may be used simultaneously, and are then capable of handling a great range of possible situations. This is done in SENSOR, with $a_1 = 0.6$, $a_2 = 0.4$, and approximations of CAPRI inside NEMESIS by a combination of non-linear functions (land demand in agriculture) and constants (total production and demand in agriculture, price index of agriculture). The iterative solution of the models, including convergence promoting extensions and computation of measures of convergence, should – in view of the immense computation time required – be fully automated. It does unfortunately not fit within the scope of this text to treat technical solutions to automation of the models.

5 Model linkages in SENSOR

Figure 2 shows how the model components NEMESIS, DYNA-CLUE, CAPRI, and EFISCEN are linked. The description of the iterative linkages can start with any of the models in the chain. In practice, the chain starts with CAPRI, since CAPRI assumes the role of controlling the whole chain. For didactic reasons, we start the description with NEMESIS.

NEMESIS determines the land use by sector according to the scheme described in section 2 and in the NEMESIS model description. The resulting land allocation for each of the sectors, on member state level, is denoted by the vector A, and is sent to DYNA-CLUE. DYNA-CLUE disaggregates the land use down to 1 km² grid units, and adds the land cover types recently abandoned arable land, recently abandoned grassland, (semi)natural cover, forests and stable areas. It also distinguishes permanent crops from rotational crops. It then re-aggregates to sub national regions: the land available for agriculture A_a on NUTS-X level, including fallow land, is passed on to CAPRI, and forest area A_f is sent to EFISCEN (for each EFISCEN region).

CAPRI also receives, directly from NEMESIS, the vector of input price indices W, technical progress index vector T, and consumer expenditure vector Y. CAPRI uses those together with the agricultural land amount A_a to compute a new set of parameters, i.e. to create a new set of input prices, consumer expenditure and land constraints.

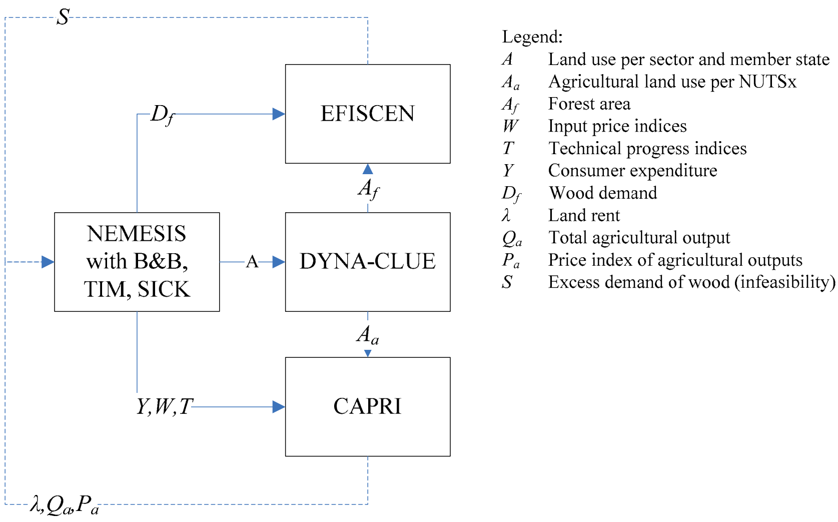

Fig. 2. Flow chart of model linkages. B&B, TIM and SICK are included in NEMESIS.

CAPRI also receives, directly from NEMESIS, the vector of input price indices W, technical progress index vector T, and consumer expenditure vector Y. CAPRI uses those together with the agricultural land amount A_a to compute a new set of parameters, i.e. to create a new set of input prices, consumer expenditure and land constraints. This implies shifting the CAPRI input prices, GDP and land constraints from the baseline values in proportion to the changes in the NEMESIS and DYNA-CLUE results. The coefficients of proportionality are computed in a differential baseline calibration approach and are referred to above as "link ratios". CAPRI also implements a partial adjustment mechanism, with two lags and the factors 0.6 and 0.4 as described in the previous section, to safeguard against rare cases where the shocks between subsequent iterations are too big. After finding a new solution, CAPRI aggregates the dual values for land λ to the member state level, and also computes gross production of agriculture Q_a and the Laspeyre's price index of agriculture P_a, and sends this back to NEMESIS.

EFISCEN receives national demand for wood D_f, from NEMESIS and forest area A_f from DYNA-CLUE. D_f is converted into physical units and from A_f changes in forest area are calculated, which are added or subtracted from the forest area in EFISCEN. EFISCEN then assesses whether the demand for wood can be satisfied and projects forest resource development. A feedback (S) is sent from EFISCEN to NEMESIS as a percentage deviation between D_f from NEMESIS and the wood removals by EFISCEN at the national level. NEMESIS uses these results from EFISCEN to constrain D_f so that it cannot exceed the demand for which EFISCEN was run. In this way NEMESIS and EFISCEN do not need to iterate. The cost of wood production may change and NEMESIS calculates a new balance between imports and exports of wood within the EU and new values for net imports outside the EU. All wood that cannot be harvested according to EFISCEN, will be imported from outside the EU.

NEMESIS uses the information from CAPRI, i.e. the land price (λ), total output of agriculture (Q_a) and agricultural price index (P_a) to recalibrate the land demand function for agriculture, and also replaces its equations for total agricultural output and one price equation by *constants* corresponding to the results (Q_a,P_a) from CAPRI. The land demand function for agriculture in NEMESIS is determined by equation (2) below[11], where, for each iteration i, λ^i is the land price, C^i_{others} an index of other agricultural inputs cost, A^i is the land demand for agriculture and c^i and b are parameters.

$$A^i = c^i \left(\frac{C^i_{\text{others}}}{\lambda^i} \right)^b \tag{2}$$

Agricultural land prices per country (λ) are endogenous variables in CAPRI and NEMESIS and an iterative procedure is necessary to find the joint equilibrium land price in CAPRI and NEMESIS. When NEMESIS begins iteration i, the land demand is shifted in such a way that, if considered alone, at the land demand (A) and others inputs cost (C_{others}) sent to CAPRI in iteration $i-1$, it would have returned the actual CAPRI land rent in iteration i. This implies computing c^i as shown in equation (3):

$$c^i = A_a^{i-1} \left(\frac{C^{i-1}_{\text{others}}}{\lambda^i} \right)^{-b} \tag{3}$$

[11] In fact, the land demand function in NEMESIS is more complex, because NEMESIS is a dynamic model. The variable A denotes the long term desired level of land, and it enters with a time index in another equation with partial adjustment from period t-1.

NEMESIS is then solved including the re-calculated parameter c^i (see equation 3) in equation (2), with agricultural output and price index fixed to the last solution of CAPRI.

We conclude this section with some words about the technical implementation: In practice, the different models run on different institutes and are implemented in different software. Data exchange takes place in the form of files written to an FTP-server on the internet. The models regularly check the server to determine if a simulation is required, and in that case, download the output of the other models, recomputed parameters, simulate, and upload the new results. In that way, the rather time consuming computations can proceed with very little human intervention. In general, convergence in one simulation is achieved within a handful of iterations. Since CAPRI and NEMESIS presently both require about an hour for each iteration, and DYNA-CLUE much more, a typical simulation requires about a day of computation time.

6 Discussion

In SENSOR, a general method was developed that in theory seems capable of linking five sector models, one macro model and a land cover disaggregation model in a consistent way. In practice, not all components of a theoretically sound linkage could be established. Whereas it appears to be theoretically possible to link all variables where there is an overlap between models' outputs or where the output of one model serves as input in another, only a handful of such links could be implemented within the present project. In particular, linkages of prices of labour and capital, external trade, and the input structure of agriculture are still absent. Below we explain why these linkages are absent, and what could possibly be done about it in the future.

Prices of labour and capital are endogenous in NEMESIS, whereas they are only implicitly present in the parameters of CAPRI. CAPRI does not have labour and capital as explicit inputs, but works with gross value added. Furthermore, CAPRI uses a method derived from Positive Mathematical Programming (see e.g. Howitt 1995) to calibrate the agricultural supply module to observations and to impose a realistic supply behaviour. The calibration method together with the lack of labour and capital in the model implies that the costs for labour and capital are embedded in a lump sum costs term, which is really a behavioural term also containing all other factors influencing producer supply behaviour. To properly link the models, this cost term should be shifted, so as to reflect changes of prices of labour and capital in NEMESIS. Since labour and capital uses are not explicit in CAPRI, the size of the possible error is difficult to assess.

Both NEMESIS and CAPRI feature endogenous external trade. Since CAPRI has a comparatively sophisticated trade model, the external trade of agriculture in NEMESIS should be linked with that in CAPRI. This has not been done, and the differences in external trade between CAPRI and NEMESIS can now serve as a "quality measurement" of the linkage. Due to the time constraints in the project, this has not been done.

Finally, CAPRI contains a much more detailed technology of agriculture than NEMESIS, and is thus capable of delivering more precise forecasts of changes in inputs. Use of inputs by the agricultural sector is endogenous in NEMESIS and information from CAPRI is presently not exploited in NEMESIS. Similar to the case of external trade, the difference in agricultural input use between the models could be (but have not been) evaluated ex-post in order to assess the size of the possible error.

7 Summary

This chapter described the coupling of five sectoral models to one macroeconomic model and one land cover model. Linking these models allows for a consistent, multi-scale and multi-sectoral assessment of important land use change processes. Though not a fully theory-consistent link could be implemented in SENSOR, the system still provides significantly extended capabilities compared to the stand-alone models. Most importantly, the system captures the essential ingredients of the competition for land by different sectors. Policies that are directed towards any individual sector inevitably affect the regional land balance, and thus all other land-based sectors. However, land balances are not the only links implemented in the SENSOR modelling approach. Other linkages are e.g. between CAPRI and NEMESIS input prices and GDP (see Figure 2). With the linked system presented here, the impact at sector level of general economic policies and developments can be analysed. Hence, analysis of, for example the simultaneous impact of bio-energy policies on the energy using and producing sectors inside NEMESIS, wood removals and forest resource development in EFISCEN and agricultural production in CAPRI, becomes possible. Another important property of the system is the possibility to link sector policies to national innovation policies. In one SENSOR scenario, namely financial reform of the common agricultural policy (CAP), this strength is utilized to obtain improved measures of and insights into the opportunity costs of the CAP by analysing the effects of transferring funds now spent on agricultural support to national innovation (R&D) policies, and assessing the impact on national income, rural land use and agricultural income. Who will gain from such a transfer, who will lose and what will be the overall impact on the economy, are questions that can be analysed with the model system. Last but not least, the process of developing the system has lead to accumulation of new insights in the principles of model linking, which may prove beneficial not only to SENSOR but also in a wider perspective.

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