Integrating Biophysical and Socio-Economic Models for Land Use Studies

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1. Introduction

Understanding the dynamics of land-use change is a scientific challenge of considerable importance to humanity. The demands for improved knowledge of environmental processes and the impacts of policy on their dynamics must increase, as population pressures on food supplies and natural resources mount and the publicly held perception of preserving environmental diversity and amenity strengthens. Some of the most profound changes in the landscape have arisen from direct decisions by man concerning land use: from changes in cropping patterns, afforestation and deforestation to modification of watercourses. These in turn have affected both the quality of environmental resources and the sustainability of a lasting and diversified food chain.

The convergence between economic viability and environmental protection is perceived by both the scientific community and the policy maker as being an important component of land use sustainability. Furthermore, there is growing realization that rapid land use change is resulting from policy and economic influences (*e.g*. CAP reform) as well as changes in the physical environment, such as the climate. Thus, integration of biophysical and socio-economic approaches to land use research underpins the success of the policy-informing process. However, the realization of this perception and its development into a coherent research strategy is not easy. Mainstream research has traditionally adopted approaches only relevant to individual disciplines and the difference in methodologies between disciplines has tended to preclude integration of approaches within single research projects.

The IMPEL project (Integrated Model to Predict European Land use) seeks to overcome a number of these difficulties. IMPEL, which is funded by the Commission of the European Communities under the Framework IV Programme (Climate and Environment - DGXII), aims to integrate physical and socio-economic modeling procedures to evaluate the impact of climate change on European land use systems at the regional scale. As a spatially distributed model, based on a multidisciplinary, modular approach, the IMPEL modules require the formal coupling of different modeling approaches. This coupling needs to overcome several difficulties including the need to:

- operate at different temporal scales in view of the constraint of data availability and reliability for different modeling approaches;
- operate at different spatial scales, *e.g*. land use decisions based on profitability are made at the scale of the farm enterprise, whereas biophysical soil and plant processes are described for individual fields or soil map units;

- introduce feedbacks, *e.g*. farm-scale land use allocation models define optimum crop rotations based on (amongst other factors) crop productivity, but crop yields are themselves influenced by the preceding crop because of carry-over effects on available water and nutrients.

This paper seeks to discuss the difficulties arising from the integration of biophysical and socio-economic models, for land use studies, and to outline the methodology adopted by the IMPEL project that attempts to overcome these difficulties. The paper is illustrated with examples from the UK.

2. The Modular Approach

One of the difficulties in undertaking multidisciplinary research is communication between researchers with a wide range of views, approaches and terminologies. The differences often arise because a variety of modeling methodologies may be appropriate for each disciplinary aim. In order to overcome this problem the development of IMPEL was based on a formal modeling framework that facilitates the integration of the different modeling approaches. The principal aim of this framework was to identify the key information items that need to be exchanged between the modules. This approach allows freedom for individual modellers to develop modules using approaches that are most appropriate and acceptable to their discipline, provided the module inputs and outputs are compatible with the requirements of the overall framework.

The key IMPEL modules are illustrated in Figure 1., and comprise:

- A **climate module** (named EuroSCEN) to downscale baseline climate data (gridded to 0.5° Lat/Long) and GCM climate change scenario datasets, using a stochastic weather generator.
- A **soil and crop module** (named ACCESS, AgroClimatic Change and European Soil Suitability) to evaluate the soil water balance and crop yields for a wide range of European crops at the scale of soil map units. Complex soil hydraulic properties (e.g. water retention, hydraulic conductivity) are derived from pedotransfer functions.
- A **land degradation module** to evaluate the impact of soil erosion and changes in soil quality on crop productivity at the scale of soil map units. The module uses mechanistic approaches to simulate surface runoff and decision trees to accommodate the influence of management practices.
- A **socio-economic module** to evaluate optimal land use allocation and management requirements at the scale of individual (generic) farms. The module is based on linear programming and assumes farmers make land use decisions that maximize profitability whilst averting risk. The module takes account of farm sizes, existing farm systems, and other demographic factors. This enables predictions of the likely rate of change of land use, based on the difference in profit between existing and proposed systems caused by variations in yields, prices, soil workability and resources such as irrigation.
- A **hydrology module** to evaluate runoff at the catchment scale.

This paper focuses on the interrelationships between the climate module, the soil and crop modules and the socio-economic module, and so these are described in more detail below.

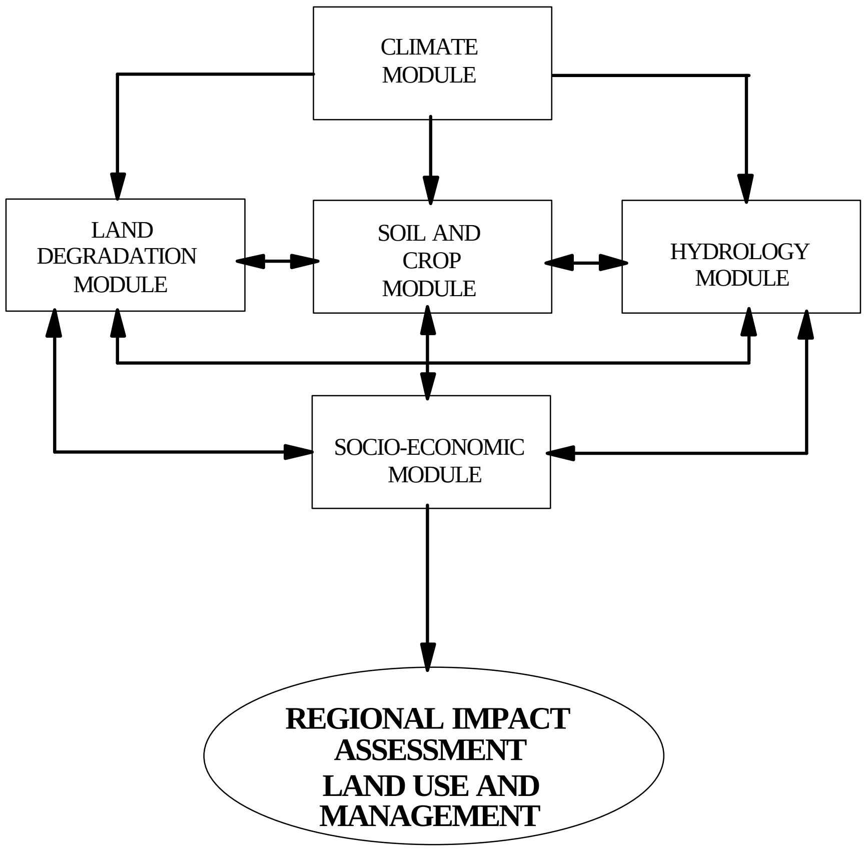

Figure 1. The modular structure of IMPEL.

2.1 The climate module (EUROSCEN)

EUROSCEN is a simple software tool that enables the user to exploit results from both simple and global climate model experiments, combined with European climatologies, to construct a range of geographically explicit future climate change scenarios for Europe. The software framework allows the user to explore the consequences for these scenarios of adopting different assumptions about climate system parameters and emissions scenarios and of selecting results from different global climate model (GCM) experiments. The simple and global climate models used by EUROSCEN have all been used or reported by the IPCC, most of them in the latest 1995 Second Assessment Report (IPCC, 1996).

EUROSCEN is driven by in-built global-mean temperature projections derived from MAGICC 2 (Model for the Assessment of Greenhouse gas Induced Climate Change). It uses six greenhouse gas emissions scenarios (IS92a-IS92f) and three values for the climate sensitivity: 1.5°, 2.5° and 4.5°C. For the European window, (defined as 35-68°N and 15°W-45°E), EUROSCEN allows the user to generate scenarios of climate change for any future dates up to 2100 at 5° resolution for mean, minimum and maximum temperature, diurnal temperature range, precipitation, cloud cover, vapour pressure and windspeed. These scenarios can be determined from a suite of fourteen GCMs (four transient and ten equilibrium experiments), based either on individual GCMs or on user-selected composites. The composite scenarios allow uncertainty ranges around a central estimate to be displayed. These change fields can be superimposed onto a European baseline climatology to generate 'actual' climatologies for future periods at 0.5° spatial resolution. An option to display actual baseline climatology representing the 30-year period 1961-90 also exists.

For any displayed scenario and for any selected subregion the user can request an output file to be created which will contain the actual scenario data - these files can then be used as inputs into other analyses, *e.g*. into weather generators (see below). On-screen maps can be saved as a postscript files and imported to any document or printed. The final version of EUROSCEN is expected by August 1997.

A weather generator, named SWELTER (Synthetic Weather Estimator for Land use and Terrestrial Ecosystem Research), has been developed which allows up to 18 weather parameters to be estimated at the daily scale, using the monthly data provided by EUROSCEN as inputs. SWELTER is a stochastic-deterministic weather model that generates synthetic time series of a small number of physically interpretable phenomena (rainfall, temperature, *etc*.). These time series are robustly estimated from limited climatic statistics, derived from instrumental data. In other words, series will have the same 'intrinsic' properties as the instrumental meteorological data from which they are derived. The weather generator facility is currently being coupled with the observed baseline information provided by EUROSCEN, to develop synthetic scenarios of weather suitable for use in the other IMPEL modules (*e.g* the Potential Soil Moisture Deficits, PSMD given in Figure 2).

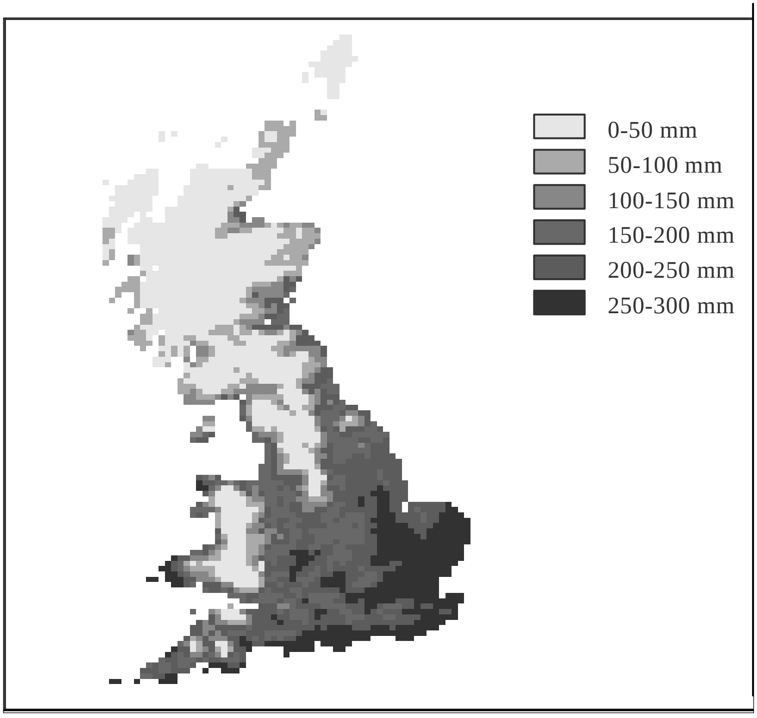

Figure 2. Application of SWELTER in GB under current climate (1960-1990 baseline) to calculate the potential soil moisture deficit (PSMD) at a resolution of 10 km.

2.2 The soil and crop module (ACCESS)

The soil and crop module is based on the ACCESS model (AgroClimatic Change and European Soil Suitability) (Loveland *et al*., 1993; Armstrong *et al*., 1996; Mayr *et al*., 1996; Rounsevell *et al*., 1996). ACCESS simulates soil hydrology and crop growth for a wide range of crops over large geographic areas using spatial soil, climate and topographic datasets. Both annual (*e.g*. wheat, maize, barley, sunflower, soya bean, potatoes, sugar beet and oilseed rape) and perennial crops (*e.g*. grass, woodland and orchards) can be modeled using different modeling approaches, *e.g*. light use efficiency, water use efficiency or physiological dry matter production. A range of other relevant biophysical processes are simulated, including canopy interception, snow formation and snow melt. The particular modeling approach used depends on the availability of spatial data and on the geographic size of area considered: simpler models are used for larger areas. Pedotransfer functions facilitate the spatial application of ACCESS (Simota and Mayr, 1996). These functions are used to estimate complex soil hydraulic properties (the water release curve and saturated hydraulic conductivity) from simple, but reliable, soil survey data (particle size distribution, bulk density and organic carbon content).

An example of data derived from the application of ACCESS is given in Figure 3. The graph shows the distribution of simulated winter wheat yields for the period 1981 to 1990, in a region of central, southern England that is approximately 170 km by 170 km. Rasterized soil and climate datasets were used at a spatial resolution of 1 km. The range of yields shown in Figure 3, result largely from the differences in soil types within the study region.

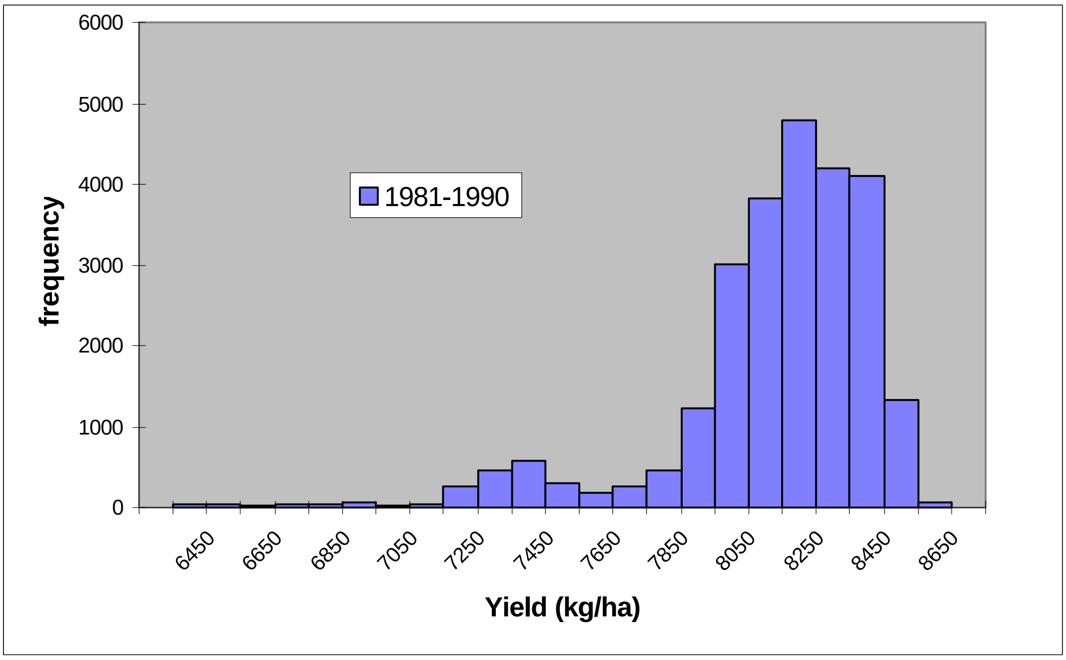

Figure 3. The distribution of winter wheat yields simulated by ACCESS for the period 1981 to 1990.

2.3 The socio-economic module (ARABLE)

The socio-economic module is based on the use of linear programming (LP) techniques to evaluate optimum agricultural land use (at the farm scale) for a range of European environments, including the need for machinery and farm labour and the timing of machine operations (Audsley, 1993). The module estimates land use decisions by considering non-significantly different near-optimal solutions and the cost of change: increasing the area of an existing crop will have no penalty, but introducing a new crop would have a start-up penalty.

The socio-economic module requires a number of inputs, including crop yield and its variability, and soil workability, which are derived from ACCESS. A summary of the input variables to the socio-economic module is given in Table 1. The socio-economic module also accounts for farm sizes, existing farm systems, and other demographic factors to enable predictions to be made of the likely rate of change of land use, based on the difference in profit between existing and proposed systems. The variability in yield and prices are used to determine a profit risk profile. The module can be used to assess the capacity of different agricultural systems to adapt to climate change and, more importantly, identify which systems will be slow or unable to adapt.

Table 2 illustrates data derived from the use of the socio-economic module for a combinable crop model farm in England and for a range of soil types (Armstrong Brown *et al*., 1996). In this example of a single farm, the linear program has been used to evaluate the optimum cropping areas that a farmer would adopt under different policy conditions. The present is represented by the year 1990, the situation before reform of the Common Agricultural Policy (CAP), and the post-CAP reform year is 1994. The model assumes no change in crop yields between these dates, nor any other economic condition.

Table 1. Summary of input variables for land use optimisation (the socio-economic module)

	Variables
Crop	Gross margin: yield (primary and secondary), prices, seed rate, fertilizer rates, sprays and costs
	Husbandry operations: list of operations and their feasible timing *e.g*. plough, cultivate, drill, spray, fertilize, harvest, bale
	Timeliness penalties: extra cost or loss of yield of doing operation at other than the optimal timing
	Rotational penalties: reduction in yield from one crop following another, including impossible
Operations	Workrate as a function of size of machinery and amount of *e.g*. yield or fertiliser or soil type
	Workable hours as a function of soil type, rainfall and time of the year
	Machinery needed (*i.e*. size, power)
Machinery and labour	Cost: capital, repairs, fuel, resale value
	Replacement interval

Table 2. Optimum crop areas (ha) for a 300 ha combinable crops model farm in England at pre (1990) and post (1994) CAP reform prices (after Armstong Brown et al. 1996)

Crop type	**Soil textural type**							
	Sand		**Loam**		**Heavy Loam**		**Clay**	
	1990	1994	1990	1994	1990	1994	1990	1994
Winter wheat	190	166	140	125	128	109	122	112
Winter barley	80	35	79	45	86	58	92	50
Spring barley	0	1	40	34	31	26	22	16
Peas	0	22	11	21	26	32	34	42
Winter oilseed rape	30	13	23	6	5	0	19	21
Spring oilseed rape	0	17	7	24	26	30	11	9
Set-aside	0	45	0	45	0	45	0	50

3. Discussion: Module Integration

The key challenge for the IMPEL project is the successful integration of the modules into a single computer framework. This approach simply requires that the inputs and outputs of the different modules are compatible with one another. The key inter-module linkages between the soil and crop and socio-economic modules are:

- primary yield,
- soil type,
- workable hours as a function of soil type and climate,
- the effect of rotations on soil, *e.g*. soil water contents, N status,
- fertiliser and irrigation effects,
- monthly soil moisture content.

These data are generated for the empirically based socio-economic module by the process-based soil and crop simulation module. The effect of preceding crops on the soil water balance and N status is very important in the soil/crop simulations, especially for southern Europe. It is necessary to run the soil and crop models for each crop following each other crop, in order to generate data to inform the socio-economic module. A major assumption underpinning the modeling framework is that of optimization. It is assumed that all farm level production systems aim to achieve maximum profitability by optimizing yields and minimizing production costs. It is also important to note that simulated crop yields are generally larger than actual observed (farm) yields because the simulation models reflect the biological optimum, and farmers rarely achieve this. In the UK, on average, farmers achieve 75% of the optimum (Van Lanen *et al*., 1992), although this value changes throughout Europe, and diminishes sharply in less technologically developed countries. When studying climate change impacts, the over-estimation of yields is less of a concern because it is the relative change in yields, between the baseline and a climate change scenario, that is most important.

The problems of nitrogen and irrigation are similar. The best approach is based on the use of response curves, although it is necessary to shift the position of these response curves in relation to a change in the climate. Response curves can be generated by the soil and crop module through simulations assuming different levels of inputs. The generated response curve can be used to define the economic optimum of inputs, which is important in the evalution of on-farm profitability by the socio-economic module.

Scale (both temporal and spatial) is an important consideration for integrated modeling. The soil and crop module operates at the scale of individual soil types, whereas the socio-economic module must operate at the scale of individual farms because these represent the enterprise level at which land use decisions are made. IMPEL is applied by assuming that the basic spatial modeling unit is the farm, which comprises one (or more) soil types. The assessment of land use change at the regional or national scale is then undertaken by aggregating the results for many individual farms within a region. This ‘bottom-up’ approach enables the variability of soil, climate and farm types to be treated explicitly by the model.

4. Concluding Points

The development and application of IMPEL has illustrated a number of key points for integrated land use studies:

- further exploration should be made of appropriate methodologies and models that tackle the problem of integration (especially interfaces between biophysical and behavioural information) which at the same time address the problem of scale (both spatial and temporal);
- because of the need to integrate information at different scales priority should be given to the development of combined databases for use in cross-disciplinary research;
- a 'bottom-up' approach has the flexibility to encompass the variability of soil, climate and farm types within a region or country, which reflect variability in yields and profit;
- the onus is on the research community to use integrated studies to better appreciate the perspectives and requirements of different sectors, i.e. the research community perspective is only a single sector focus in its own right;
- integrated land use studies can provide a research framework within which a range of policy-relevant issues and further insight into complex systems can be addressed. Integrated studies should, therefore, be given a higher priority in national and European-wide research programs: a process that may require the re-evaluation of 'traditional' sectoral boundaries, and a commitment from funding organizations to sponsor non-conventional research projects.

5. Acknowledgements

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6. References

Armstrong, A.C., Legros, J-P. and Voltz, M. (1996. ACCESS-II: a detailed model for crop growth and water conditions. *International Agrophysics*, 171-184.

Armstrong Brown, S., Rounsevell, M.D.A., Annan, J.D., Phillips, V.P. and Audsley, E. (1996). Agricultural policy impacts on UK nitrous oxide fluxes. *Proceedings of the Workshop on Mineral Emissions from Agriculture*, Oslo, Norway, January 1996.

Audsley, E. (1993). Labour, machinery and cropping planning. In: Farm planning. Labour and labour conditions. Computers in agricultural management (edited by Annevelink, E., Oving, R.K. and Vos, H.W). Proceedings XXV CIOSTACIGR V Congress Wageningen, Netherlands. Wageningen Pers, pp. 83-88.

Hulme, M. , Raper, S.C.B. and Wigley, T.M.L. (1995) An integrated framework to address climate change (ESCAPE) and further developments of the global and regional climate modules (MAGICC) *Energy Policy*, **23**, 347-355

IPCC (1996) Climate change 1995: the science of climate change (eds.) Houghton, J.T., Meiro Filho ,L.G., Callendar, B.A., Harris, N., Kattenburg, A. and Maskell, K. Cambridge University Press, Cambridge, UK, 572pp,

Loveland, P.J., Rounsevell, M.D.A., Mayr, T.R., Legros, J-P, Voltz, M., de la Rosa, D. and Armstrong, A.C. (1993). ACCESS: AgroClimatic Change and European Soil Suitability - a spatially distributed model. In: *Climate Change and Impacts* (I. Troen, ed.). EUR 15921 EN, pp. 215-228.

Mayr, T.R., Rounsevell, M.D.A., Loveland, P.J. and Simota, C. (1996). Agroclimatic Change and European Soil Suitability: regional modeling using monthly time-step data. *International Agrophysics*, **10**, 155-170.

Simota, C. and Mayr, T.R. (1996). Predicting the soil water retention curve from readily-available data obtained during soil surveys. *International Agrophysics*, **10**, 185-188.

Rotmans, J., Hulme, M. and Downing, T.E. (1994). Climate change implications for Europe: an application of the ESCAPE model. *Global Environmental Change*, **4**, 97-124

Rounsevell, M.D.A., Loveland, P.J., Mayr, T.R., Armstrong, A.C., de la Rosa, D., Legros, J-P., Simota, C., Sobczuk, H. (1996). ACCESS: a spatially-distributed, soil water and crop development model for climate change research. In: (R.J. Froud-Williams, R. Harrington, T.J. Hocking, H.G. Smith, T.H. Thomas, eds.). *Implications of global environmental change for crops in Europe*. Aspects of Applied Biology No. 45., pp. 85-92. ISSN 0265-1491.

Santer, B.D., Wigley, T.M.L., Schlesinger, M.E. and Mitchell, J.F.B. (1990). Developing climate scenarios from equilibrium GCM results. Max Planck Institute fur Meteorologie, Report No.47, Hamburg.

Van Lanen, H.A.J., Van Dieppen, C.A. Reinds, G.J. de Koning, G.H.J., Bulens, J.D. and Bregt, A.K. (1992). Physical land evaluation methods and GIS to explore the crop growth potential and its effects within the European Communities. *Agricultural Systems*, **39**, 307-328.