An integrated modelling approach to conduct multi-factorial analyses on the impacts of climate change on whole-farm systems.

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Abstract: Climate change impact studies on whole-farm systems require a holistic approach due to the complexities of biophysical processes, management and inter-relationships of land use within a single farm. This paper details the process of utilising a multiple-objective, strategic land use planning tool to conduct multi-factorial analyses on the impacts of climate change at the farm scale. Two example sites are given to illustrate the flexibility of the method: an upland mixed sheep and suckler cow farm in Scotland, with cold wet winters and cool moist summers; and a combined cropping and indoor reared beef farm in Italy, with cool moist winters and warm dry summers. The approach allows the additional risk that climate change may introduce to the farm system to be quantified. Model output facilitates the development of adaptation and amelioration strategies. This Integrated Assessment (AI) approach employs the Land Allocation Decision Support System (LADSS), a framework which permits a wide range of counter-factual assessments of financial, social and environmental impacts of changes to policy, management and biophysical conditions. The framework contains a Geographical Information System (GIS) and relational database linked with land use models, impact assessments and planning tools. Crop based land uses are represented by the CropSyst cropping systems model and livestock by a Livestock Production Model (LPM). The framework provides an opportunity to explore the linkages between sub-components of the farm system and demonstrates the diversity of possible climate change impacts. The paper indicates the importance of management decisions in determining amelioration of the impacts of climate change on the farm system. Farms constitute one of the fundamental units within the agri-ecosystem, hence it is important to understanding the impacts of change and the subsequent requirements for management adaptation. This understanding can then be used to better inform policy makers.

Keywords: Climate change impacts, multi-factorial analyses, farm systems, LADSS, CropSyst.

1. INTRODUCTION

The impacts of climate change (CC) may manifest themselves on whole-farm systems in many ways, ranging from subtle, small-scale cause and effects, to extreme events, with both occurring simultaneously. It is desirable to know which is more influential in determining a farm's viability and capacity to adapt. The intricacies of both scales of impacts require a detailed modelling framework, which should be able to represent the complexities of biophysical processes, land use inter-relationships and management regimen. Such a framework enables a holistic IA approach to determine the impacts of CC throughout the farm system. Previous studies have identified potential CC impacts for a range of farm components, e.g. individual crops at the national scale (Holden *et al* 2003), site-specific cropping systems (Tubiello *et al* 2000), milk yield and dairy herds (Topp and Doyle 1996), and crop yields and ecosystem processes (Izaurralde *et al* 2003). Studies carried out on cropping systems in Europe include: Bindi *et al* (1999); Bellocchi *et al* (2002); Donatelli *et al* (2002). However, to complete a holistic study of CC impacts, it is necessary to include the consequences on the biophysical components, inter-relationships between land uses, and the subsequent financial and social aspects. It is desirable to know whether there is sufficient flexibility and resilience within a farm system to cope with the impacts of CC, and what adaptation and amelioration strategies will be required. Strategies to cope with CC are most likely to be facilitated through changes in management practises, to both individual land uses and the overall farm system. Using the framework output, a soft-systems appraisal approach can be taken (e.g. Matthews *et al* 2002), where practitioners identify potential adaptation and amelioration strategies. These strategies can then be created as new scenarios run within the framework to determine how they respond to CC.

This paper describes the structure of a framework consisting of the Land Allocation Decision Support System (for full details see LADSS website, http://www.mluri.sari.ac.uk/LADSS/ladss.shtml) which has been adapted to enable studies of the impacts of CC. Two contrasting locations and farm systems are given as examples of the flexibility of the framework: one a mixed sheep and suckler cow system in central Scotland (Hartwood); the other is a combined cropping and indoor reared beef farm in Tuscany, Italy (Montepulciano).

2. FRAMEWORK STRUCTURE

LADSS (Matthews *et al* 1999) enables farm-scale multi-objective land use planning, considering financial, social and environmental constraints. The system determines a range of optimal land use patterns for a given set of constraints, e.g. financial return versus land use diversity. Additional outputs include financial, social and environmental impacts for each optimised land use pattern. This enables detailed counter-factual analysis across a broad range of inter-relationships. The framework consists of a Geographical Information System (GIS) linked to an Oracle Relational Data Base Management System (RDBMS). Land use systems are represented by simulation models: CropSyst cropping systems simulation model (Stöckle *et al* 2003) and a Livestock Production Model (LPM) which simulates sheep and cattle systems. A simple forestry model represents trees grown on the farm. Land use system models estimate a range of variables including productivity for areas within a farm that have the biophysical attributes required to support them. The models are linked to a package of integrated impact assessments: financial; social and environmental and a genetic algorithm based land use planning tool. The social impact assessment contains a Resource Scheduling Tool (RST) (Matthews *et al* 2003) which is linked to the RDBMS and land use models. The timing of management events is then used to schedule labour and machinery requirements, with associated cost being calculated by the RST and financial assessment. Data are supplied from the RDBMS to the land use systems models and impact assessments. Spatial data detailing the farm layout are supplied from the GIS. The database and GIS also perform analysis on the stored data and those returned by the land use model components.

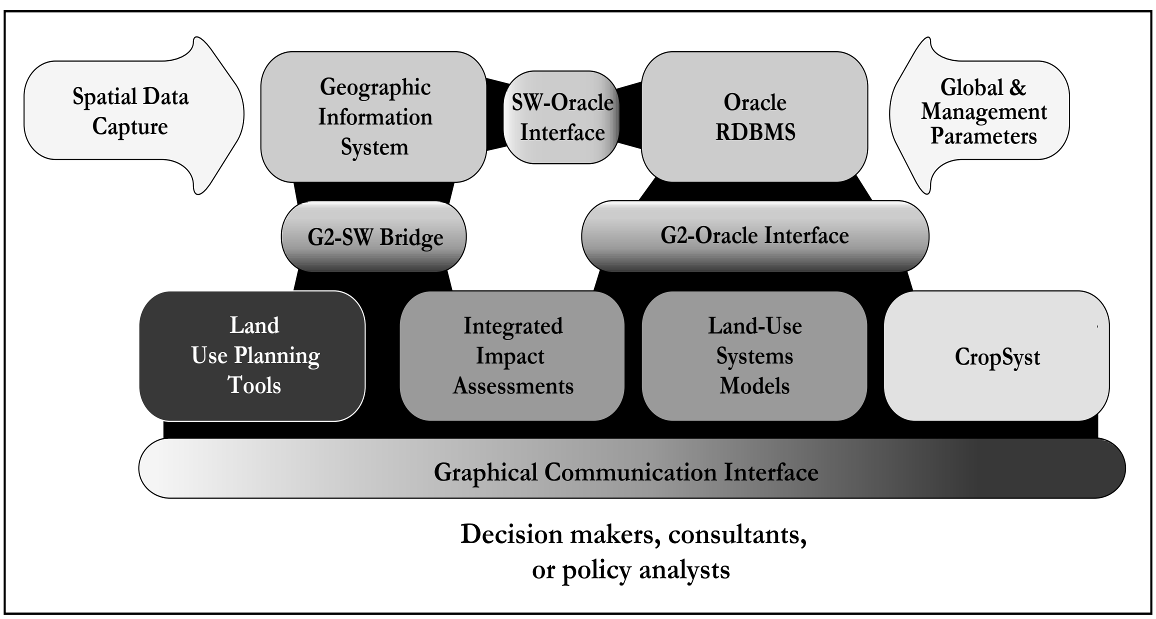

Figure 1. LADSS component structure with input elements. SW refers to SmallWorld GIS and G2 is a knowledge base development software.

2.1 Framework requirements

The framework requires a detailed set of inputs describing the variability of biophysical characteristics, the management regimen and associated costs and revenues within the farm. Spatial data are captured from aerial photography which is also used to define in-field soil sampling strategies. This facilitates cost effective soil data collection and permits identification of homogeneous areas of soil. In modelling crop production, daily precipitation, air maximum and minimum temperature and solar radiation data are used within CropSyst, hence a requirement for site-representative data. The LPM requires information about the livestock management and feed regimen.

2.2 Spatial configuration

The spatial configuration of farm resources is important as it serves to identify the biophysical and practical constraints on management. These help determine the boundaries of adaptation and amelioration strategies. A farm within the framework exists in four object classes in a hierarchy:

- Land block fragment polygons (LBFP) are the smallest unit and are used to calculate spatial geometry within the GIS.
- The land block fragment (LBF) are areas of biophysically homogeneous land, which also have a uniform management regime. Soils exist in multiples of layers within an LBF. The LBF is the lowest level at which financial analysis is conducted.
- Land blocks (LB) are areas of homogeneous land use and the scale at which the land use system models are applied.
- An Enterprise (farm) is made up of land blocks and forms the top level of the hierarchy, for financial, social and environmental analysis and auditing.

2.3 Farming systems coverage

The flexibility of the framework can be illustrated by detailing two contrasting farm systems in diverse locations which are currently represented by LADSS. Hartwood Farm in Scotland is a 350 ha mixed sheep (c. 500) and cattle (c. 200) system, representative of upland farms in marginal production areas in upland central Scotland. It is characterised by cold wet winters and cool moist summers. Mean annual rainfall is about 1200 mm, maximum and minimum mean monthly temperatures are 17 and -2º C respectively. Elevation ranges between 150 to 300 m a.s.l. with south facing slopes. Soils are shallow, poorly drained gleys which rarely fall much below field capacity, making the farm difficult to work in wet conditions and susceptible to poaching. Prolonged wet periods prevent machine access to fields. The soil shows high within-field spatial variability. Field boundaries are irregular shapes and non-systematic, being artefacts of previous ownership (Fig. 2). Winter wheat and spring barley is grown as whole crop fodder. A farm such as Hartwood would typically be family run, equivalent to employing 3 staff.

The farm in Montepulciano, Italy, is a 300 ha combined cropping and indoor reared beef system, with cool moist winters and warm dry summers. Elevation is about 300 m a.s.l., with no slope. Maximum air temperatures are often higher than 35 ºC. Average annual rainfall is about 700 mm, mostly concentrated in spring and autumn. Field boundaries are uniform and systematic (Fig. 2.). Crops grown include: cereals (durum wheat), forages (alfalfa, triticale), oil-seed (sunflower) and horticultural (capsicum, tomato) root (sugarbeet) and leaf crops (tobacco). Livestock activity is the breeding of Chianina cattle (c. 300 animals), reared for meat production and reproduction, organised as partially free housing in stalls. Livestock manure is applied directly to the fields. Deep soils have been artificially created as a result of the saturation of the antecedent wetland sediments from flooding. Semi-permanent and permanent water bodies make up 10 hectares of the farm, providing reservoirs for crop irrigation. The volume of such reservoirs can be estimated to determine the irrigation capacity. There is a high irrigation demand in the spring and summer. The farm is family run with 6 permanent staff, 2 of which are devoted to livestock management. Temporary staff are employed at harvesting and transplanting times.

2.4 Excluded considerations and limitations

There are limits to the considerations made in a holistic study. In the examples given it is not possible to assess animal welfare and conseqential labour requirements, crop quality etc. External influences acting on the farm, such as new policies, changes in commodity prices etc. although able to be represented, are currently considered as fixed for this type of study.

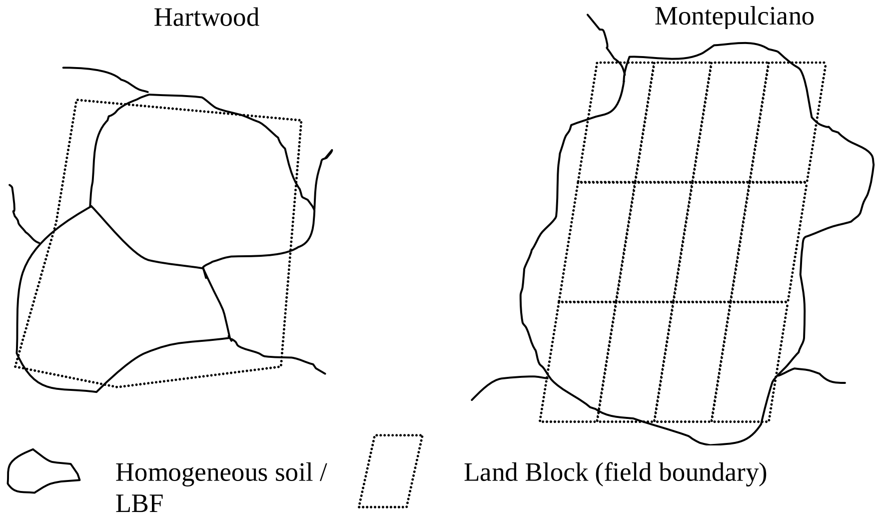

Figure 2. Relationship of soil variability and field boundaries between Hartwood and Montepulciano farms

2.5 System adaptations

It is important to know the variability of soil resource distribution given the requirements to estimate the impact of CC on farm productivity and consequences on management. There are substantial differences in the spatial configuration of soil variability in relation to the shape and size of LBF between the two example farms. At Hartwood the soils are highly variable within large irregular shaped fields (therefore fields with multiple LBFs), whereas at Montepulciano LBFs are small, regular shaped and can exist within relatively uniform soil conditions (Fig 2). The differences between the two sites required that changes be made to the GIS and RDBMS structure. By making the LB to LBF a 'many-to-many' relationship within the database allows an LBF to be part of many LB, reducing the number of land use model simulations made per LBF. In the example of Fig 2, land use models are applied to each LBF: for Hartwood the results of land use model simulations are aggregated between the LBF to give a single set of values for the LB; at Montepulciano the simulation is applied for a single LB and the results replicated for other LBs within the same LBF.

3. EXAMPLE CC SCENARIOS

The framework is able to use daily CC scenario weather data from a wide range of sources representative of different scales. For example from general circulation models (GCM), statistical downscaling, or weather generators. For case studies, a basic analytical approach entails the introduction of estimates of CC induced alterations and examination of how the framework estimates differs from the a base solution without climate change. Simulations can be run for transient scenarios drawn from two GCMs, the Canadian Climatic Centre (CCC) model and the Hadley Centre (HAD) model. Although impact analysis can be based on these transient scenarios, it is preferable to use average climate conditions for periods around the year 2030 or 2090. Long-term observed daily weather records form the basis to generate 50 years of baseline and altered climate data sets, by using the ClimGen (Stöckle *et al* 2001) stochastic generator. Average productivity and resource use can then be estimated over this 50 year period for the baseline and altered climate scenarios. Use of CropSyst to estimate crop biomass enables atmospheric CO_2 concentration levels to be set that represent the time period and CC scenario being simulated, e.g. 350 ppmv for the baseline; 445 ppmv for 2030, and 660 ppmv for 2090 IS92a scenario of future emissions (IPCC 2000).

4. FRAMEWORK OUTPUTS

For a no CC scenario (baseline) the framework can produce a range of optimised patterns of land use for a given set of constraints. Maintaining these constraints and then using weather data from the CC scenarios permits between-scenario comparisons. Responses to CC can be observed for each individual land use (e.g. change in yield), biophysical entity (e.g. soil water and nitrogen balances) and whole farm (change in land use patterns). Outputs also need to indicate changes in the levels of risk associated with CC per land use and their role within the whole farm system. For each of the patterns of land use per scenario, associated labour and machinery requirements (from the RST), financial and environmental impact assessment outputs are produced. Outputs can be visualised in both the GIS (maps of the spatial allocation of land uses) and G2 interface (RST, social, environmental and financial impacts), allowing practitioner appraisal. This permits identification of potential management adaptations and amelioration strategies.

4.1 Potential biophysical impacts of CC

Weather is the primary variable determining the soil/crop state and influences the ability of farmers to respond with appropriate management. Weather determines biophysical relationships such as soil and crop water and nitrogen balances, phenological development and ultimately biomass accumulation e.g. as modelled by CropSyst. Changes in climate will lead to altered weather inputs resulting in different responses of the biophysical relationships, e.g. evapotranspiration and rainfall input, thermal time accumulation etc. and subsequent levels of crop production.

There are numerous pathways in which CC affects the soil/crop/livestock processes and overall farm system. Analysis of effects such as impacts on crop yields, water demand, water supply, and livestock production, using biophysical models can inform us of why a particular climate scenario causes yields to rise or fall and suggest directions for adaptation at a range of scales within the farm. Within the framework, it is possible to analyse at least three principal direct effects of CC:

- Crop yields
- Water supply and irrigated crops, soil water balance
- Livestock performance and grazing / pasture supply

Impacts on each of these determine the new set of resource use levels. These elements can be investigated via the frameworks output.

4.2 Potential CC impacts on whole farm systems

Observation of the impacts on crop phenological development (due to altered air temperature conditions and impact on thermal time accumulation) indicate the shifts that can occur in the timing of management events. The impacts of this are picked up by analysis of the RST output. For the dry Italian farm, determining the changes in soil water balance and crop water uptake for all crops enable estimates to be made of irrigation demand. This amount compared with the estimated total irrigation capacity permits identification of potential shortages. Such analysis permits the identification of potential requirements to invest in increased irrigation capacity. For the wetter Scottish farm, changes in days when the land is workable due to soil water-logging can be identified.

The relationship between the ability of a farm to produce fodder for the livestock system determines the herd size. Changes in farm produced fodder crop quantity can be modelled within the framework, but not the impacts on feed quality. The consequences in altered fodder crop biomass production can therefore be partially identified through analysis of the outputs from the LPM.

Utilising the land use pattern optimisation capability of LADSS permits GIS maps to be drawn of potential future patterns of land use within a farm. This enables the visualisation of how patterns of land may change over a period of time.

5. DISCUSSION

The framework described is able to establish the relationship between CC impacts on biophysical processes functioning at the within-field scale and the consequences on land use productivity and subsequent farm-scale financial, social and environmental values. The framework is sufficiently flexible to allow a wide range of farm systems in diverse locations to be represented.

Holistic IA approaches to studying CC at the farm-scale need to consider the points at which the weather impacts manifest themselves. Changes to patterns in weather and quantities of variables can impact on soil water and chemical balances and subsequent crop growth characteristics. Alterations to livestock feed capabilities, access to land and timing of turn-out dates determine herd sizes, nutrient and energy flows and overall productivity. Changes in areas that can support land uses within a farm at a given threshold of productivity can be identified, as can land uses that are subject to increased risk. The output from the system is strongly influenced by the input weather data. The emphasis then falls on the quality of the CC scenario weather data. However the flexibility of the framework permits a wide range of CC scenarios to be represented. The manipulation of input weather data provides the opportunity to simulate a wide range in the frequency and magnitude of extreme events and their impacts. This permits the identification of a scale of importance of the impacts, e.g. the relationship between infrequent extreme events and subtle continuous alterations to the biophysical environment. Impacts of extreme events may be beyond a farm's capacity to adapt, but the framework output may indicate how the frequency of these events affects its overall viability due to the increased risk.

6. CONCLUSSION

This type of IA approach permits the pre-emptive identification and testing of appropriate CC impact adaptation and amelioration strategies. Farmers, land managers and policy makers can then be better informed in constructing management methods and policies that will assist in coping with CC. The flexibility of the framework, as illustrated by the two farms detailed here, will enable the identification of the variability in impact scales for a diverse range of farm systems and locations.

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8. REFERENCES

Bellocchi G., C. Maestrini, G. Fila, F. Fontana. Assessment of the effects of climate change and elevated CO_2: a case study in Northern Italy. VII European Society for Agronomy Congress, 15-18 July, Cordoba, Spain, 763-764. 2002.

Bindi M., M. Donatelli, L. Fibbi, C.O.Stöckle. Estimating the effect of climate change on cropping systems at four European sites. Proceedings of the 1st International Symposium Modelling Cropping Systems, 21-23 June, Lleida, Spain, 147-148. 1999.

Donatelli M., F. Tubiello, U. Peruch, C. Rosenzweig. Scenarios of climate change effects on sugar beet in Northern and Central Italy. Ital. J. Agron., 6, 133-142. 2002.

Holden, N.M., A.J. Brereton, R. Fealy, and J. Sweeney. Possible change in Irish climate and its impact on barley and potato yields. *Agric. For. Meterol.* 116, 181-196. 2003.

IPCC, Special Report on Emissions Scenarios, http://www.grida.no/climate/ipcc/emission/index.htm). 2000.

Izaurralde, C.E., N.J. Rosenberg, R.A. Brown, A.M. Thomson. Integrated assessment of Hadley Centre (HADCM2) climate-change impacts on agricultural productivity and irrigation water supply in the conterminous United States Part II. Regional agricultural production in 2030 and 2095. *Agric. For. Meteor.* 117, 97-122. 2003.

Matthews, K.B., A.R. Sibbald and S. Craw. Implementation of a spatial decision support system for rural land use planning: integrating GIS and environmental models with search and optimisation algorithms. *Computers and Electronics in Agriculture* 23, 9-26. 1999.

Matthews, K.B., K. Buchan, A.R. Sibbald and S. Craw. Using soft-systems methods to evaluate the outputs from multi-objective land use planning tools. Integrated Assessment and Decision Support: Proc. Int. Environmental Modelling and Software Society, 24 - 27 June, University of Lugano, Switzerland, Vol. 3, 247 – 252. 2002.

Matthews, K.B., K. Buchan and A. Dalziel. Evaluating labour requirements within a multi-objective land-use planning tool. MODSIM 2003 Int. Congress on Modelling and Simulation, 14-17th July, Townsville, Australia. 2003.

Stöckle, C.O., R. Nelson, M. Donatelli, and F. Castellvi. ClimGen: a flexible weather generation program. Proc. 2nd Int. Symp. Modelling Cropping Systems, 16-18 July, Florence, Italy. European Society of Agronomy. 2001.

Stöckle, C.O., M. Donatelli, and R. Nelson. CropSyst, a cropping systems simulation model. *Europ. J. Agronomy* 18, 289-307. 2003.

Topp C.F.E., and C.J. Doyle. Simulating the impact of global warming on milk and forage production in Scotland: 2. The effects on milk yields and grazing management of dairy herds. *Agric. Syst.* 52, 243-270. 1996.

Tubiello, F.N., M. Donatelli, C. Rosenzweig and C.O. Stöckle. Effects of climate change and elevated CO2 on cropping systems: model predictions at two Italian locations. *Eur. J. Agron.* 13, 179-189. 2000.