INSIGHT into Biophysical Models for Evaluating Alternative Land Use Policies in Eastern Australia

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Abstract: CSIRO Sustainable Ecosystems is constructing a spatially explicit modelling system capable of exploring the implications of land use policy alternatives under plausible price and climate scenarios for the next 20 years. In this paper we report on the biophysical modelling components of this project, including sub-models of agricultural production and hydrology. We discuss the purpose and design of each model and the challenges encountered in combining the different components, and recommend future steps in the evolution and integration of the biophysical components of INSIGHT. The purpose of the agricultural sub-models is to provide a one-dimensional model of how climate, soil and management interact and affect the productivity and environmental impact of agricultural systems. The agricultural models are then nested within a spatial model of the regional level processes including river salinisation, biodiversity decline, and agricultural profitability and adjustment. Agricultural models have been developed to simulate wheat and pasture-sheep production. The hydrology model is designed to link changes in land use with changes in groundwater recharge, river flow and river salt loads. While there exists a large amount of crop, pasture and hydrology modelling capability, there are several problems to overcome in developing sub-models for this purpose. The computational demands of a spatial-temporal analytical framework mean that relatively simple models are required. Simplicity is also required if the model is to achieve its main objective which is to provide regional level policy makers with a strategic overview of the workings of the catchment system. These requirements need to be balanced against the problems of working in a data-poor environment which, at least in the short-term, make it necessary to base the model on mostly mechanistic functions. A further issue is the need to integrate biophysical models where different levels of data and modelling capability exist. Finally there is a need to validate the sub-models. Further work is required to find the most efficient way to utilise the existing knowledge and modelling base to do this, and to establish processes for identifying the main dimensions and range within which validation is required.

1. INTRODUCTION

CSIRO Sustainable Ecosystems is developing a spatially-explicit modelling system, known as INSIGHT, to explore land and water policy alternatives in the Lachlan River Catchment of New South Wales. This will enable the analysis of biophysical, social and financial impacts over the next 20 years of adopting different policies. The objectives and philosophy of the INSIGHT framework have previously been described [Walker and White 1999; Gorddard and Walker 2001].

INSIGHT is a framework for integrating economic and ecological information in a manner that respects the principles that have been developed by economists and ecologists. The vision presented is one of a dynamic modelling system that is spatially explicit and future-oriented.

INSIGHT is concerned with providing policy makers with timely integrated economic, social and environmental information and with procedures for asking "what if" questions about the likely impacts of policy changes. As such it is aimed at increasing insight into and understanding of the system rather than at predicting future developments.

2. INITIAL DEVELOPMENTS

Walker and White [1999] discussed progress in the development of INSIGHT focussing on two key initiatives: a systemic description of current models of crop production, grassland systems, economic systems, degradation and water balance; and the production of a "demonstrator" version.

The first step was completed by White and Walker [2001] who published flowcharts setting out the key components of published models of crop, pasture and other agricultural systems. These included models dealing with aspects of land degradation and land management. White and Walker also proposed an approach to summary crop and pasture models which was a starting point for the versions of the agricultural models described below. Initially it was planned to run these against monthly climate data, but this time step, which might be adequate for very extensive grazing systems in arid areas, is inappropriate for the pasture and cropping systems under study. It was therefore decided to take daily climate data, primarily rainfall, maximum and minimum temperatures, and pan evaporation, and integrate these by weeks so that the crop and pasture models can be run with a weekly time step. A daily time step was perceived as desirable from the point of view of the crop and pasture models, as will be discussed later on, but was not seen as desirable for the catchment model, given the computational demands of a multiyear spatially explicit and multiple issue model. Nested time steps will probably solve this tension between aggregation levels.

Currently complete catchment scale models of the water cycle are not available for this region, however this is an active area of research. Our approach was to link existing models of components of the system together in a simple and transparent manner. The impact of land use on evapo-transpiration is based on Vertessy and Bessard [1999]. This is linked to work on river flows [New South Wales Department of Land and Water Conservation, 1999] and river salinisation [Beale et al., 2000].

3. OVERVIEW OF BIOPHYSICAL SUB-MODELS

The models were developed using the Ventana Simulation Language [VENSIM®] [Ventana Systems Inc.; http://www.vensim.com].

At this stage agricultural modelling is confined to simulating the growth of pasture or cereal crops. Assuming that the pastures are C_3 grass-dominated, it is therefore focussed on *graminaceae*, which may be either annual (e.g. annual ryegrass, wheat) or perennial (e.g. perennial ryegrass, phalaris) species. Both the crop model and the grassland model use the water balance as described in the next section.

3.1 Water Balance

The soil is assumed to be comprised of three layers, total depth depending on the soil type. The primary role of the upper layer is to determine when annual pasture or crop species will germinate in response to adequate soil moisture (typically in autumn or early winter), and whether the emerging seedlings will survive. It is also the most important soil layer for soil evaporation. The middle layer usually contains the bulk of the plant roots, so that its moisture content is a major determinant of plant growth. The bottom layer is assumed to extend to the lower limits of root growth, or a further 1 metre in depth.

A tipping-bucket model is used to simulate water movement down through the soil profile. Water in the upper soil moisture zone is determined as the sum of weekly rainfall less losses due to energy-limited evaporation, upper level transpiration and 'upper percolation' from the upper down to the middle zone. It is assumed that water evaporates from the upper horizon only, following a modified two stage approach [Ritchie, 1972]. Actual transpiration is determined primarily by the level of crop-limited transpiration, the amount of moisture in the different soil layers, the moisture capacity of these respective layers, and the root index that specifies the proportion of roots in each soil layer.

Downward movement of water through the soil profile is determined on a weekly basis as excess water above the drained upper limit in each layer. Loss of moisture from the bottom layer of the soil moisture is assumed to be deep percolation, the magnitude of which can be crucial in the search for more sustainable farming systems. The model does not predict any upwards movement of water due to either capillary rise or water table fluctuations.

3.2 Crop Growth and Yield

The wheat crop model was based primarily on using key elements of the southern wheat crop model of O'Leary and Connor [1996] and the I-Wheat model of Meinke et al. [1998].

A typical sowing window is defined for winter wheat, depending on time of the year and soil moisture in the upper soil layer. Phenological development of the plant is based on degree days, using a base temperature that varies with the stage of development. Degree-day requirements for emergence, anthesis and maturity are cultivar dependent.

Biomass production is estimated as the minimum of radiation-limited dry matter production and water-limited dry matter production. Radiation-limited dry matter production is the product of the fraction of solar radiation intercepted, radiation use efficiency and solar radiation, where the fraction of solar radiation intercepted is asymptotically related to the leaf area index (LAI). The extinction coefficient that determines the shape of this relationship is itself related to the LAI, but also varies with the stage of crop development [Meinke et al., 1998].

Water-limited dry matter production is the product of transpiration efficiency and actual transpiration. Transpiration efficiency is a function of daily (weekly) evaporation [Fischer, 1979]. Crop-limited transpiration from each soil layer in this study is adjusted according to leaf area index, and the proportion of roots estimated to be in that layer. Actual transpiration from the various soil layers is assumed to be reduced at low levels (<30 %) of soil moisture availability [O'Leary and Connor 1996].

The accumulation of above-ground biomass depends on both biomass production, biomass allocation to the roots and losses through senescence associated with aging and water-stress of the crop.

The weight of the developing kernel is a function of the amount of above-ground plant biomass at anthesis (via the translocation), plus production post-anthesis and the maximum Harvest Index. The maximum HI depends on the maturity type of the cultivar and on water stress (the latter is not yet implemented in the present version).

3.3 Grassland Production

The proposed model draws on elements of both the DYNAMOF [White et al., 1983; Bowman et al., 1993] and GrassGro [Moore et al., 1997] pasture models.

The upper soil moisture layer, described above, is critical for areas of southern Australia with annual grasses and legumes (clovers, medics), particularly in determining the timing of the autumn break. Pasture species germinate in response to autumn rains, but seedlings die if follow-up rains fail to occur. This signifies a false break.

The potential growth rates of pasture for each week of the year are determined by solar radiation and temperature, consistent with the GrassGro pasture model of Moore et al. [1997]. The parameters are influenced in part by the pasture mix in each shire, based on data from the national pasture survey (NSW). Evaporation from the soil surface depends on the cover of green and dead herbage and litter, evaporative demand as determined from measured pan evaporation, and the amount of moisture in the soil [White et al., 1983; Moore et al., 1997].

Soil moisture is utilised by being transpired via plants, total plant transpiration being a function of total evaporative demand (potential evapotranspiration), and the amount of available soil moisture in each soil layer. Evaporative demand from each soil layer is a function of leaf area index (LAI) and the extinction coefficient, and the proportion of roots estimated to be in that layer. The proportion of solar radiation (PRAD) intercepted increases to an asymptote with increasing LAI.

3.4 Livestock Intake, Maintenance and Growth and Wool Production

Two herbage classes are assumed, green and dead, as per White et al. [1983]. The digestibilities of these classes vary over time, in response to availability and soil moisture status for green and dead herbage respectively. The voluntary intake of herbage is estimated relative to the availability and digestibility of the herbage and the live weight of the sheep. The decision to feed supplements is invoked when the mean weight of the wethers falls below a specified minimum value. The quantity fed depends on the availability and feed quality of the herbage and on the decline in herbage intake that occurs when feeding supplements to sheep. Total herbage consumption depends on the choice of stocking rate, this being based on data from NSW Agriculture and the Australian Bureau of Statistics.

The metabolisable energy requirements of sheep for maintenance and growth are estimated as per White et al. [1983]. The efficiencies of utilization of metabolisable energy for maintenance, and for growth and fattening, vary with the metabolisable energy concentration of the diet.

The functions for estimating wool growth are those of Bowman et al. [1993] whereby equilibrium wool production is linearly related to the sheep's relative energy intake, weekly wool production calculated assuming effects of body condition and a 25 day lag response to changing nutrition. Flocks are characterised according to their potential fleece weight, upper limit to intake and maximum possible weight, potential wool production also varying due to photoperiod with time of year. Changes in mean fibre diameter are linked to changes in mean fleece weight, these being of the order of 1.5 to 2.2 μm/kg for Merino sheep [White and Morley, 1977].

3.5 Soil Acidification

The model aimed to estimate the changes in soil pH that are likely to take place under different agricultural systems at different locations throughout the catchment. The soil is characterised by an initial soil pH, and a soil pH buffering capacity reflecting the organic matter and clay content of the soil [Helyar et al., 1990]. Net acid addition rates are based on the estimates of Helyar and Fenton [pers. comm.] for different forms of agricultural production and bioclimatic regions. These rates are based on data collected from systems operating at a moderate N fertility status and where there was no hay or silage removal. The option exists to adapt the model to account for levels of nitrogen fertility, forms of nitrogen input and amounts of alkalinity removed in hay and silage. Changes in pH over time are a function of net acid addition rates and soil pH buffering capacity, and an Acid Addition Rate Index that is a function of Soil pH [Helyar and Fenton, in preparation].

The initial estimates of net acid addition rates of cropping systems in all but the driest regions are 6 kmol H^+/ha/year, equivalent to 300 kg lime/ha/year [Helyar and Fenton, pers. comm.]. Values of 2-3 for perennial pastures and 1.5-4.0 for annual pastures are also proposed. Other values for acid addition rates in the region of interest are those of Moody [report to Land & Water Australia, in preparation].

The option exists to add lime. The adjustment for liming is ('added lime (kmol)'/soil pH buffering capacity)/neutralising value. The effect of soil pH on plant growth follows Hackett and Harris, [1996].

It is recommended that the next version of the model allows changes in soil pH to vary with soil depth. This is important since roots are unlikely to penetrate soil layers with extreme pH levels, and the impact of lime is greatest near the soil surface.

3.6 Native Vegetation

We model the impact of native vegetation area and condition on the water balance, biodiversity, and agricultural production. The area and condition of vegetation are modelled over time for each land unit. Condition of native vegetation in the model declines unless it is fenced to control grazing. The model permits planting and fencing of new areas of native vegetation. Vegetation condition improves with time following planting or fencing. The impact of native vegetation on production, is a function of vegetation area and condition [Ivey ATP, 2000]. Species diversity is thought to be a function of patch size and condition [Freudenberger and Drew, 2000]. However a model of biodiversity conservation is not developed, rather the area of protected vegetation is used as an indicator of conservation outcomes. The reasons for this are that the links between conservation activities and conservation outcomes are highly uncertain. In addition defining measurable and meaningful conservation outcomes depends on the conservation objective. In future work we hope to utilise information on the distribution of current and pre-existing vegetation types [Austin et al., 2000] in conjunction with community defined revegetation objectives to define regional level conservation outcomes.

4. LINKING POINT MODELS TO THE REGIONAL MODEL

Relating models of point changes to changes at large spatial scales is a nontrivial task. At a minimum there is a need for spatial data on the modelled variables. A wide range of omitted variables can potentially affect the modelled relationships differently across space. Various landscape level interactions can also affect the aggregate impacts. Frameworks such as material budgets [Raupach and Moran, 1998] provide some structure when scaling up, however the expense of large scale experiments means there will often be poor data and large uncertainty about the aggregate impact of land use changes. Our current method for scaling up uses available spatial data to spread point processes across the catchment. The aggregated effect under model conditions is compared to model results under historical conditions, and this ratio is used to scale existing catchment scale data. We now describe how the point models of crop and pasture water use are linked to catchment scale models of hydrology and salt mobilisation.

4.1 Catchment Scale Hydrology

The water balance model links the water use of different land use options for each land unit within a sub catchment to the rate of rise in groundwater and changes in flow levels in the Lachlan river. Rainfall is partitioned between evapo-transpiration and excess water, which is further partitioned between net stream flow (base flow plus runoff) and net groundwater rise (recharge minus base flow). The rate of rise of groundwater is then linked to the model of river salinisation described below.

Excess water is partitioned between stream flow and ground water rise in proportion to the historical ratio. However the model also permits incorporation of more detailed modelling processes that take account of the partitioning of stream flows between runoff and base flows, time lags in groundwater movement, and landscape scale complexities.

Rainfall data come from the Silo Data drill [Jeffrey et al., 2001]; groundwater data from the NSW DLWC bore measurements in the catchment are those of Beale et al. [2000]. Stream flow data are derived from the Integrated Quantity and Quality model of river flow developed for the Lachlan river [NSW DLWC 1999] The catchment scale model of Vertessy and Bessard [1999] determines the fractions of excess water that are attributed to vegetated land and cleared agricultural land. For cleared agricultural areas, the impact of land use on excess water is calculated using the point models of agricultural production. Specifically the ratio of excess water under new land uses compared with historical land use is used to scale the volume of excess water coming from cleared agricultural land.

4.2 River Salinisation

The effects of groundwater rise on river salinisation are calculated using the methodology developed for the Salinity Predictions for NSW [Beale et al., 2000]. The rate of ground water rise drives this model. First the distribution of groundwater levels and the rate of rise determine the rate of increase in the area of land that is mobilising salts to the surface (ground water within 2 metres of the surface). This area, the rate of ground water rise and the salt concentration determine the amount of salt potentially mobilisied for each type of geology within each subcatchment. The geology determines the amount of water and salt within the ground. River salinity loads are modelled as increasing in proportion to increases in this potential salt load. It is intended that later and more sophisticated models of salt balances can be linked into the INSIGHT model as required and as they become available.

5. DISCUSSION

The agricultural models presented in this paper are components of the integrated catchment model. The major purpose of the crop, grassland and sheep production models (incl. the water balance) is quantification of 1) evapo-transpiration and excess water which are used as input for the catchment hydrological model; 2) agricultural productivity in physical and economic terms; and 3) the relationship between agricultural production and soil degradation (i.e., soil acidification). For the purpose of the INSIGHT project, the idea was to develop minimal models which sacrifice the precision and detail of specialist models but maintain the logic of the bio-physical processes.

Development of a minimal model (meta- or summary models are terms with similar connotations) can be done in several ways. One way would be to develop such a model based on an understanding of the basic ecological principles determining production, summarized in (semi-) mechanistic equations and tested extensively against empirical data. A second option [see for example Brooks et al., 2001] is to develop a simple model from a more complicated one. This can be done through systematic sensitivity analyses and identifying the most relevant aspects of the system, with specific reference to the conditions for which the simple model should be applicable. The simplification of an existing model can give confidence by extensive cross-validation against the original model.

Neither of these options were feasible in this project. Extensive data sets with crop and pasture growth for the Lachlan catchment were lacking, and we did not have operational and tested crop or pasture models for the Lachlan catchment at hand. We therefore opted to develop simple models based on existing models that have not been tested in the Lachlan catchment. The developed models need to be validated against empirical data.

The agricultural models as presented are more mechanistic and detailed than the models for catchment hydrology and natural vegetation. A legitimate question is whether the integrated catchment model is well-balanced in its components. Would more simple agricultural models or equations do the job? Is more detail in the hydrological part desired? These questions can only be answered in a rigorous validation and sensitivity analysis of the integrated model and its components. Temporal and spatial resolution will be of key importance in this analysis. Such an analysis must be carried out against scientific criteria, but, importantly, also against criteria specified by the users of the integrated model and its generated information. These users have interest in the interactions and relationships between components in the systems, rather than in exact description of processes and trends.

The presented components have been used in the prototype INSIGHT model, together with socio-economic modules. Paper three in this series will report on that integration and results of the integrated model [Gorddard, 2001].

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