LUCI in the sky with diamonds – modelling the wider impacts of land use change and intensification

Peter D. Jamieson[1], RF Zyskowski[1], FY Li[1], GS Francis[1], V Snow[2] and L Lilburne[3]

[1] New Zealand Institute for Crop & Food Research. Limited, PB 4704, Christchurch, New Zealand.
[2] AgResearch Grasslands, Private Bag 11008, Palmerston North, New Zealand
[3] Landcare Research, PO Box 69, Lincoln 8152, Canterbury, New Zealand
Corresponding author jamiesonp@crop.cri.nz

Abstract

The intensification of agricultural production, particularly close to centres of population, carries with it the risk of unwanted impacts. In many cases, the major risk is the contamination of water supplies or aquifers with soluble fertilisers or agrichemicals. Land Use Change and Intensification (LUCI) is a multi-year research programme that aims to provide both the information and tools necessary to assess the likely impacts of the changing landscape on water quality. The programme involves a substantial modelling component with multiple objectives. The LUCI framework model operates at the single paddock scale but will track soil conditions, drainage and leaching over any sequence of crops and pastures through many years. The individual crop models that are available within the LUCI framework are also made available as tactical management tools that allow farmers to optimise their use of N fertiliser and irrigation, maximising their profit while minimising the environmental impacts. LUCI also contributes to a partnership with other research providers (Integrated Research for Aquifer Protection, IRAP) that includes a whole farm model and an aquifer model. Hence LUCI is the first link in a chain of models that can be used to assess the likely downstream impacts of changes in land use that may not be apparent for many years.

Introduction

Changes in land use and the intensification of agricultural production have been happening for a long time. For example, Canterbury, on the east coat of New Zealand's South Island, was once dominated by dryland sheep production. This land use has slowly changed over the years to extensive arable production. The introduction of irrigation technology together with a substantial increase in the amount of fertiliser intensified that production and, recently, there has been a substantial increase in irrigated dairy production. Some quantified examples of the changes are:

- sheep numbers declined from 70 million in 1982 to 39 million in 2002, while dairy cattle numbers increased from 3.4 million in June 1990 to 5.1 million in June 2003 (NZ Treasury, 2002; NZ Statistics, 2003a);
- the area of land under irrigation doubled every decade for the last 50 years (Agriculture NZ et al., 2000);
- N fertiliser use doubled from about 100,000 t in 1990 to about 200,000 t in 2000 (New Zealand Climate Change Project, 2002);
- increased use of water and N inputs has driven land use intensification and resulted in increased production per unit area. The amount of lamb meat produced has remained >400,000 t p.a., despite the 40% reduction in sheep numbers. Similarly, the average wheat yield increased from 3.6 t ha^{-1} in 1980 (Logan, 1983) to 7.3 t ha^{-1} in 2003 (NZ Statistics, 2003b), while vegetable growers are producing more short-term crops (PA Williams pers. comm.).

Changes and intensification in land use are an important part of regional development and are driven largely by economic factors. However, without proper management, further intensification of land use could pose a significant threat to groundwater and soil quality. For example, leaching losses of nitrate tend to be higher from more intensive land uses like dairy and winter vegetable production than from dryland pastoral farming (Francis et al., 2000). The increased use of water for irrigation leads to concerns about flow rates in surface and ground water and the concentration of nitrate in ground water (McFadden, 2001). Degradation of soil structure is also likely when soils are intensively cultivated for continuous crop production (Haynes and Francis, 1990), or poorly drained soils are compacted by cattle (Drewry and Paton, 2000).

In Canterbury, on the East Coast of New Zealand's South Island, groundwater supplies more than 90% of the drinking water, much of which is of sufficient quality not to need treating before consumption. Nevertheless, most of the region's aquifers are at risk of nitrate contamination from current and future land use. Annual monitoring in Canterbury clearly shows that land surface activities are responsible for increases in nitrate concentrations in groundwater (Hanson, 2002). Similar effects are apparent throughout New Zealand (Bright et al., 1998). Without proper management, any future intensification of land use (especially following the adoption of irrigation) could pose a significant threat to groundwater quality, especially through non-point nitrate sources. Contamination from such non-point sources is difficult to manage because the link between particular sources and their adverse effects on a water body is difficult to establish.

Into this context was born a multi-agency research partnership – IRAP. The **I**ntegrated **R**esearch for **A**quifer **P**rotection partnership aims to provide the knowledge and tools necessary for the assessment of the impacts of land activities on the quality of the soils and the nitrate content of the water in the aquifers underlying New Zealand plains areas. Thus it seeks to provide a suite of tools that deliver at different time and space scales, from single paddock to catchment, and from a timescale of a few months to many years. Briefly, the hierarchy of models is:

- the LUCI framework model – this is a model at the paddock scale than can be started arbitrarily, run for as long as necessary, and keeps track of production, the state of the soil, and the leakage of water and nitrate from the root zone. We will describe this model in more detail below;
- FarmSim (Good and Bright, 2005) – operates an assembly of paddocks at the farm scale, bound by farm system constraints of labour, machinery, irrigation capacity and the like. The model can predict the integrated effects of water and nitrate applications on a whole farm, and so will allow for differences among crops, pastures and animal loadings at that level. It can also take into account variations in soil type and management around a farm;
- Aquifersim (Bidwell et al., 2005) – a groundwater model (that integrates the effects of nitrate-contaminated recharge at farm scale, and provides information about the resulting horizontal and vertical distribution of effects in the aquifer;
- a GIS to manage spatial data that is required by the models, including land use, soil, and aquifer characteristics.

At the larger scales - farm scale and above - the models are useful for policy analysis. They can be used to address questions such as:

- What are the effects of existing land use?
- What would be the long-term effects, and where would they occur, of specific changes in land use?
- When is the long-term effect likely to occur?

At farm scale and below, it is possible to use the models as decision aids to improve crop and pasture management, with the overall aim of decreasing environmental impact without compromising production (Zyskwoski et al., 2006).

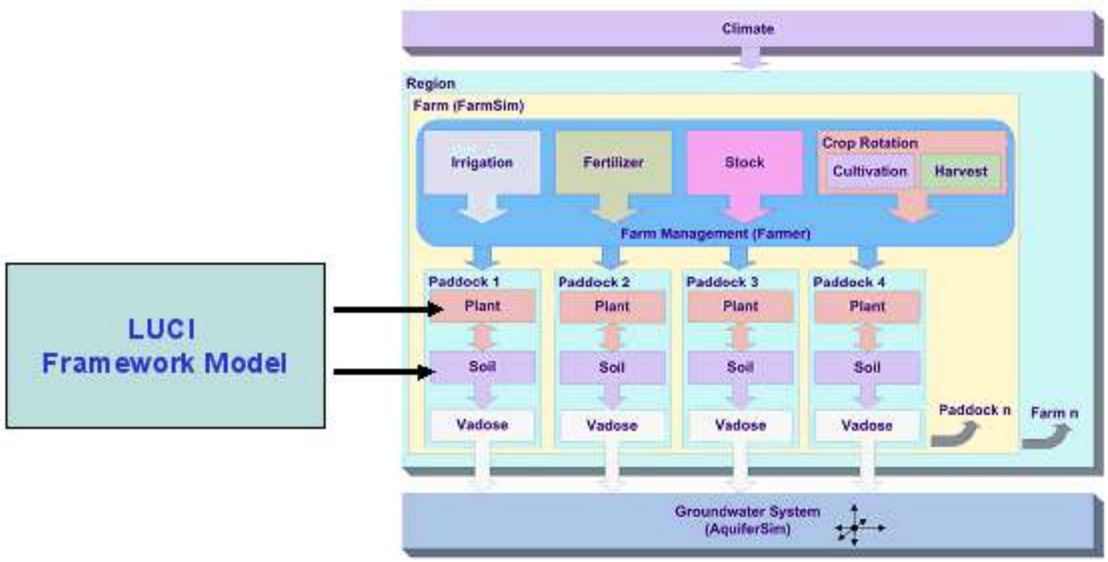

Figure 1. Relationship of the component IRAP models to one another

The **LUCI** research programme comprises both experimental and modelling objectives. The LUCI framework model is a major integrator of the knowledge generated within the experimental part of the programme. Broadly, the experimental objectives are to:

- determine the state of soils in long-term land use;

- determine the state of soils in changing land use and a description of the processes involved;

- gain a better understanding of mineralisation processes;

- provide base data on phenology, N cycling and yield determination in crops and pastures;

- measure changes in N status and N processes in water in the unsaturated zone beneath the root zone

The LUCI framework model

The major interest of the stake-holders in the programme ultimately is the nitrate concentration in groundwater. To be able to calculate that we need estimates of both the amount of nitrate entering the groundwater system and the amount of water flowing through it. The latter is the hydrological part of the programme and is addressed in AquiferSim. The former part depends on processes mostly at the surface and in the root zone. Crops and pastures are by far the biggest sink for water and N at the paddock and farm scale, and the size of the sink will depend very much on the amount of production. That means that any system for assessing N leaching needs to be able to estimate production as well as N evolution and transport. The best place to start is with a crop model. That will provide the first link in the chain of models that scale up from patch (LUCI) through farms (FarmSim) to the landscape (AquiferSim).

The LUCI framework model (LFM) is, in concept, a model of a flat paddock that can be started arbitrarily, run for an arbitrary time with any sequence of crops and pastures while keeping track of the state of the system and the leakage from it. It must produce crops or pastures, calculate the fate of fertiliser N, calculate the losses and gains of organic carbon and N and calculate mineralisation. It provides the basis for the individual paddocks in FarmSim. Our starting point was the wheat model Sirius (Jamieson et al., 1998b; Jamieson and Semenov, 2000). It contains the essential elements: a soil percolation and leaching model based on the cascade model of Addiscott and Whitmore (1991), a crop model incorporating responses to water and N, and a system for dealing with daily weather data. The original model was designed to run within a single season and used a simplified N mineralisation model that was appropriate to the lifetime of a wheat crop but not to a long sequence of seasons. So our sequence of tasks was:

- disentangle the crop, soil and weather models into individual objects;
- add a soil organic matter cycling model based on SOCRATES (Grace and Ladd, 1995) and CENTURY (Metherell et al., 1993) and test it against the simplified model;
- add other crops and pastures;
- change the timing constraints and add a fallow period between crops.

We have made substantial progress on all of these tasks, so that the LFM can now run sequences that include wheat, potatoes, maize and peas. Further models, including ryegrass/cover pasture, forage brassicas of two types (leafy and stemmy) are under development and will join the suite of models that make up the LUCI framework model (Wilson et al., 2004; Zyskowski et al. 2004).

Decision Support Systems

In parallel with the development of the LUCI framework model, itself designed to be part of IRAP (for use by policy analysts), we have been developing farm decision support systems (DSS) aimed at improving the management at the scale of a paddock . These DSSs are made up of the same models but packed so that they are very easy to use. The earliest of these was the Sirius Wheat Calculator (Armour et al., 2002), which was joined very quickly by the Potato Calculator (Jamieson et al., 2003). These have been disseminated and tested by growers through projects funded by end-user groups (NZ Foundation for Arable Research - FAR, New Zealand Vegetable and Potato Growers Federation - HortNZ), industry groups (Ballance AgriNutrients) and the New Zealand MAF Sustainable Farming fund. They have been generally well received by these groups and have some enthusiastic farmer champions. The first two have been joined by a maize calculator, known as AmaizeN, whose implementation and testing are similarly supported by FAR, fertiliser companies and the Sustainable Farming Fund.

New crop model development

Sirius, the model we started with, has undergone substantial development since it was first written in the late 1980s. That development was associated with its use as a tool for investigating processes such as phenological development (Jamieson et al., 1995; Brooking et al., 1995; Jamieson et al., 1998a) and N nutrition (Jamieson and Semenov, 2000). In that sense, it is a mature model even though it continues to be modified in the light of new knowledge. In contrast, the potato model was new. However, it has much in common with its older sibling. It has a phenological model that defines its lifetime. Linked to this is a canopy model that defines the crop’s ability to capture light. The light-use efficiency (g biomass per MJ light captured) is set to the same value as for wheat. The same simplifying assumption about N in leaves is used as in Sirius, i.e. N concentration in green matter is constant when expressed on a unit green area basis. It has a labile storage for “luxury” N in the canopy, and parasitic sinks for N (tubers) that compete with the canopy for N. The maize model is an extension of the model described by Muchow et al. (1990), as modified for cooler temperatures by Wilson et al. (1995). The extension was to include water and N limitations in very much the same way they were implemented in Sirius.

Model testing

To date there has been much more testing of the production aspects of the models than of their ability to predict the N status of soils or the amount of N leached from them. As a result of its age, there has been much more testing of the Sirius wheat model than any of the other components. Jamieson and Semenov (2000) used Sirius to simulate wheat grown in three highly diverse environments (Lincoln, New Zealand; Rothamsted, UK; and Maricopa, USA) from experiments that included variation in water and N supply, as well as atmospheric CO_2 concentration. Correlation between simulated and observed yields was very high (r = 0.95), the RMSD was quite small at 0.56 t ha^{-1} over a yield range of 3.6-10 t ha^{-1}, and the results were essentially unbiased. Good agreement of simulations with farmer yields and N uptake have also been found in New Zealand (Armour et al., 2002) for a range of cultivars, sites, sowing dates and seasons.

The potato model has been tested over several seasons but as yet has had little exposure in the literature. During the development of the Potato Calculator, test plots were set up within growers' crops at five growers per year for three years with three N regimes within each crop. The crops were monitored through the seasons, yields measured and N status of the soil measured before planting and after harvest. In particular, soil mineral N measurements at harvest in the 2004-05 season were analysed using analysis of variance. There were significant differences ($P < 0.05$) among treatments, with N higher for treatments that mimicked standard grower practice.

There was a very close correspondence between the residual N predicted by the potato model and that measured on site (Figure 1). A regression of simulated on measured residual N had an intercept close to zero, a slope near unity and high correlation ($r = 0.77$). Note – rainfall and irrigation throughout the production season were insufficient to cause any leaching – the residual nitrate-N mostly represents an opportunity for winter leaching unless it is taken up by a following crop before that can happen.

The measured range of yields from the experiments was from 55 to 87 t/ha fresh mass. Simulations tended to overestimate yields (mean bias 5.7 t ha^{-1}) and the RMSD was 9.5 t ha^{-1}. Although correlations were high over three years at two sites ($r = 0.75$ and 0.9), a very small range at other sites combined with differences among sites meant that overall the correlation was significant ($r = 0.51$, $P<0.01$) but still had substantial scatter. However, from the point of view of soil N, lower yields may still lead to greater N uptake because tuber N concentration may rise to compensate.

Impacts of variability at the sub-paddock scale

The smallest unit to be considered within the IRAP suite of models is an individual paddock – essentially a single management unit within FarmSim. However, substantial variation can exist at scales of several metres. Some of that variation may be changes in soil type within the paddock − in Canterbury alluvial soils, a major variation can be the depth of soil above the underlying gravel layers, and this is a major source of variation in root zone water-holding capacity. Machinery does not necessarily apply fertiliser evenly while irrigation systems, following fixed paths, will apply water in a systematically uneven pattern. Where crops or pastures are grazed by animals, urine patches become high concentration sources of mineral N. Such variation can be handled by using multiple simulations aggregated and weighted according to the frequency of their occurrence at the field scale. However, with the multiple sources of variation noted above, there are a large number of possible combinations. That would lead to very many simulations, which would make the operation of the models at higher scale computationally expensive. Our aim is to be able to discount within-paddock variability as much as possible by aggregation initial conditions before simulation. The question becomes, how much does simulation of the average resemble the average of the simulations?

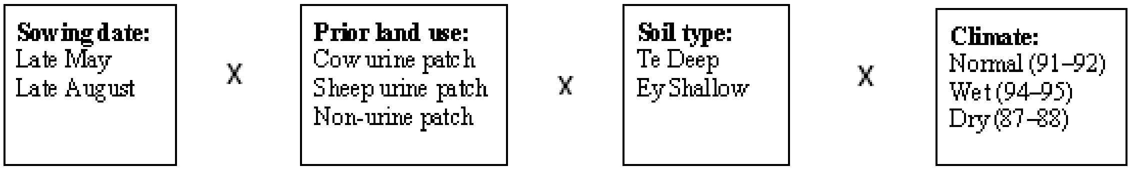

Figure 2. The set of sowing date, climate, soil, and land use options that make up the 36 scenarios.

To investigate the effect of variability at the small patch scale on the integral of N leaching at the paddock scale, we set up 36 separate scenarios of wheat production over a sequence of two years, as indicated in Fig 2 (Lilburne et al., 2006).

The effect of prior land use was to vary the initial soil nitrate content from 20 to 600 kg N ha^{-1} in appropriate proportions of the paddock. Nitrate leaching varied from a low of zero to a high of 200 kg N ha^{-1}, depending on history. This was by the far the largest source of variability and was dominated by cow urine patches. We concluded that partitioning the paddock between high N urine patches and average conditions for the rest of the paddock was sufficient to provide a reasonably accurate estimate of the paddock integral of N leaching.

The suite of models briefly described here is in early development. The most mature development so far is in the LUCI framework model, but the toolbox grows.

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