CATCHMENT-WIDE MODELLING OF LAND-USE IMPACTS ON THE RUATANIWHA PLAINS

Steve Green[1], Andrew Manderson[2], Brent Clothier[1], Alec Mackay[2]
and Monique Benson[3]

[1]The New Zealand Institute for Plant & Food Research Limited,
Palmerston North, New Zealand
[2]AgResearch, Palmerston North, New Zealand
[3]Hawke's Bay Regional Council, Napier, New Zealand

Abstract

The Hawke's Bay Regional Council (HBRC) is currently undertaking a water storage project for the Ruataniwha Plains. They are seeking information to define the potential volumes of water that are needed now, and in the future, to irrigate a range of agricultural and horticultural enterprises. In addition, the Council are also seeking information to help to assess the potential effects of land use change on surface and groundwater quality as a result of irrigating from stored water.

The current land use has been identified (using the Agribase™ and recent ortho-corrected aerial photography) as a mix of dryland sheep and beef, extensive arable, some dairy and finishing farms and a small amount of horticulture. There is also some land that is currently under irrigation. Model outputs have been simulated for these farming enterprises. The provision of a reliable supply of irrigation water is expected to change the mix and intensity of land uses and altering the environmental impacts. We are running computer simulations for a number of future farm scenarios.

Modelling is being carried out in two stages. Firstly, at the enterprise scale, we are using Plant & Food Research's SPASMO model (Soil Plant Atmosphere System Model) to simulate the daily water and nutrient balances for a range of land based enterprises, soil type and microclimates. Model outputs from SPASMO are then being imported into AgResearch's GIS landscape modelling tools to aggregate the water and nutrient balances across a number of sub-catchments (irrigation zones). The task of the enterprise-scale modelling is to assess the impacts of land use intensification on the water balance and nutrient fate. In this article, we discuss the modelling approach that is being used to simulate irrigation demand and nutrient loads from a range of land use activities. Some preliminary results are presented for selected farm enterprises.

Keywords soil water balance, land use, irrigation allocation, nutrient drainage fluxes, modelling

Introduction

The Hawke's Bay Regional Council (HBRC) is seeking information to define potential volumes of water needed now and in the future to irrigate a range of agricultural and horticultural enterprises on the Ruataniwha plains. A water-storage project is being planned for this area (Tonkin & Taylor 2009). The council is also seeking information to help them to assess the potential impacts of land-use change on surface and ground water quality and quantity. A multi-Crown Research Institute (CRI) team has been engaged in this project. AgResearch (AgR) has been assigned the task of spatially mapping and defining ‘current land use’ and land-use change scenarios for irrigable land located on the Ruataniwha Plains in Central Hawke’s Bay. Plant & Food Research (PFR) has been assigned the task of simulating the irrigation demand and nutrient losses (nitrogen (N) & phosphorus (P)) from a range of farming enterprises. Results of this modelling are then being passed on to NIWA for inclusion in a ground and surface water interactions model to predict the impact of land use intensification on the quality of the receiving waters.

The specific area of interest has been defined and bounded according to four irrigation zones (Tonkin & Taylor 2009). A fifth ‘up-stream’ zone (non-irrigated) has subsequently been added to this study in order to accommodate part of a recharge zone for the NIWA modelling (the red area in the first image of Figure 1).The purpose of this article is to provide an overview of each step of the calculation procedure that has been used to generate the water and nutrient loads. Details of the NIWA modelling are described elsewhere (Rutherford 2012).

Materials and Methods

The modelling framework

The calculation procedure involves a 4-step process, as shown in Figure 1.

- Firstly, AgR determines the current mix of soil/climate/land cover/farm type using a suite of national databases entered into their GIS landscape-modelling platform. The definition of each farm type is based on model farms described in a feasibility study of on-farm economics for the proposed Ruataniwha Irrigation Scheme, prepared by Macfarlane Rural Business Ltd (Macfarlane et al. 2011).
- Secondly, PFR models the environmental impacts of each farm type, on the receiving ground and surface waters, for a range of soils and climate zones across the Ruataniwha plains by modelling each of the enterprises that make up each farm type. Model outputs from PFR include daily/weekly/monthly totals of irrigation, soil-water drainage and runoff (mm) as well as discharges of nitrate-nitrogen (N) and total phosphorous (mg/L and kg N (or P)/ha/y) associated with each farm enterprise.
- Thirdly, model outputs from PFR are passed back to AgR for summation at the farm scale by aggregating the enterprises associated with each model farm. Enterprise scale values for water and nutrient loads are generated by combining a GIS overlay of land cover with a “look up” table of N and P discharge predictions for a combination of climates and soils and a mix of agricultural and non-agricultural land areas.
- Lastly, the enterprise scale outputs are passed onto NIWA for inclusion in a ground and surface water interactions model where the impacts on water quality are being assessed.

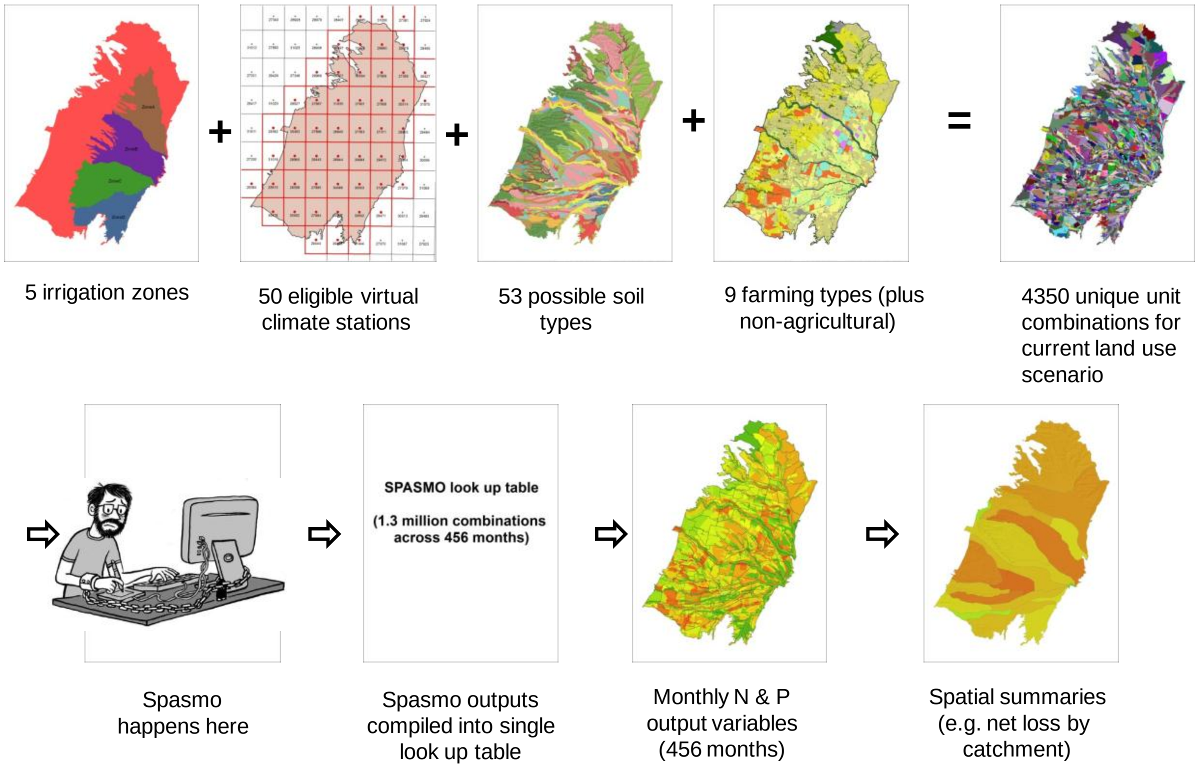


Figure 1. Modelling framework used to generate daily/weekly/monthly values of water and nutrient (nitrogen (N) & phosphorus (P)) loads associated with a mix of farming enterprises on the Ruataniwha plains.

Soil water and nutrient balance

All water and nutrient calculations have been carried out using Plant & Food Research's SPASMO model (Deurer et al. 2011; Green et al. 2008; Sarmah et al. 2005). This model considers the movement of water, solute (e.g. N and P), pesticide, and dissolved organic matter (i.e. dissolved organic carbon (DOC) and dissolved organic nitrogen (DON)) through a one-dimensional soil profile, plus overland flow of sediment and nutrients. The focus of this study is on irrigation demands and the N and P loads under a range of land use scenarios on the Ruataniwha plains.

The soil-water balance is calculated by considering the inputs (rainfall and irrigation) and losses (plant uptake, evaporation, runoff and drainage) of water from the soil profile. The model includes components to predict the carbon and nitrogen budgets of the soil. These components allow for a calculation of plant growth and uptake of N, various exchange and transformation processes that occur in the soil and aerial environment, recycling of nutrients and organic material to the soil biomass, and the addition of surface-applied fertilizer and/or effluent to the land, and the returns of dung and urine from grazing animals (Rosen et al. 2004). Model results for the water balance are expressed in terms of mm (= one litre of water per square metre of ground area). The concentration and leaching losses of nutrients are expressed in terms of mg L^{-1} and kg ha^{-1}, respectively. All calculations are run on a daily basis and the results are presented on a per hectare basis.

Climate Inputs

SPASMO uses daily values of global radiation, air temperature (maximum and minimum), relative humidity (maximum and minimum), wind speed and rainfall. These climate variables are used to calculate a daily water balance, and to grow each of the crops according to a well-defined set of allocation rules that determine dry matter production according to light interception (a function of the green-leaf area) and the availability of soil water and nutrients. Crop growth is curtailed if water and N are in short supply. Irrigation is supplied on the basis of need (Green et al. 1999). In the case of pastoral systems, the grazing management is dictated by animal feed requirements, production targets and pasture supply.

Daily values (1972-2011) of climate variables are used to calculate a local value for the potential evapotranspiration (ET_O, mm/d) using the FAO-56 Penman-Monteith model (Allen et al. 1998). The climate data are sourced from NIWA's Virtual Climate Station Network (VCSN) using the Cliflo search engine (www.cliflo.niwa.co.nz). The location of each climate station is shown in Figure 2.

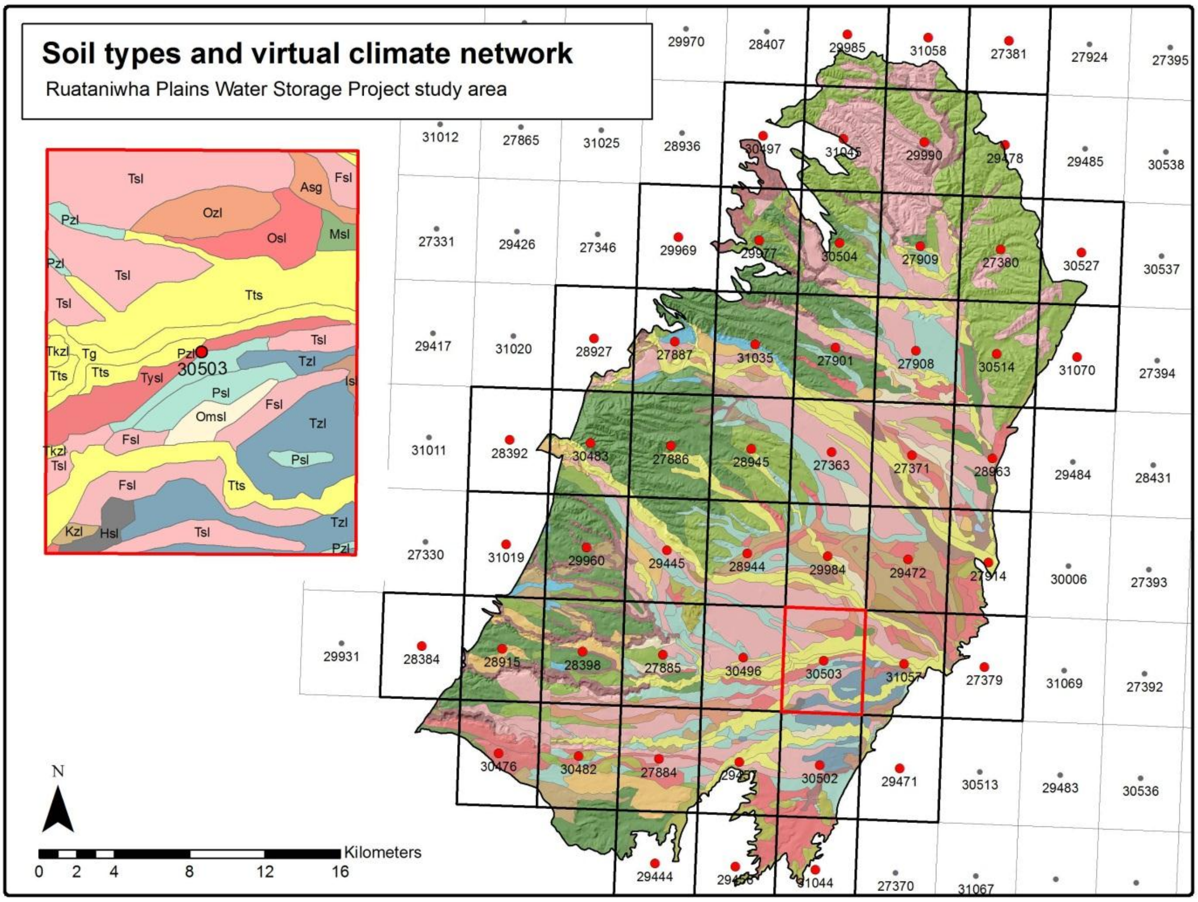


Figure 2. A GIS overlay showing the location of NIWA's Virtual Climate Network Stations (VCNS) and the map of the underlying soil series. For the purpose of modelling, daily climate data (1972-20011) were compiled and an assessment of the land area of each soil series was made for each soil grid.

Soil properties
SPASMO requires a comprehensive set of soil physical and hydraulic properties to calculate the soil water balance. It also computes the various N transformation processes that occur naturally (e.g. decomposition of plant organic nitrogen, Urea → NH_4^+ → NO_3^- → N_20 → N_2 gas), as well as those occurring following the surface-addition of water, fertilizer and/or effluent to the land. These processes are described using first-order rate constants that are moderated by the soil conditions (i.e. temperature, moisture content, C:N ratio, etc.). Three forms of mineral N (i.e. urea, ammonium and nitrate), two forms of organic N (i.e. dissolved and resident organic nitrogen) and two forms of P (dissolved reactive P and dissolved organic P) are modelled in the soil domain using a simultaneous set of equations to describe convection, diffusion and sorption of each nutrient species.

Table 1. Physical and hydraulic properties for a range of soil series found in one of the climate zone grids (NCNS30503) shown in Figure 2. Selected properties include, but are not restricted to, total porosity (TP), field capacity (FC), stress point (SP), wilting point (WP), and total available water (TAW=FC-WP). All values expressed as mm of water per m of soil.

soil series	SAT	FC	SP	WP	TAW
Argyll	210	100	62	35	65
Tukituki	193	92	39	14	79
Tikokino	345	236	172	119	117
Takapau	405	297	228	168	129
Taniwha	406	317	246	181	136
Irongate	488	285	193	123	162
Okawa	476	281	180	112	169
Mangatewai	444	368	277	190	178
Poporangi	486	413	314	218	195
Twyford	462	292	170	90	202
Omarunui	545	364	248	157	207
Flaxmere	558	365	244	151	214

Requisite soil profile properties are deduced from Landcare Research's Fundamental Soil Layers (FSL) and National Soils Database (NSDB). These properties include soil texture (sand, clay and stone content), bulk density, water-holding capacity, drainage class, and the soil organic carbon and nitrogen content. A total of 53 soil series have been identified from soil mapping of the Ruataniwha Plains (Figure 2). The soils range from extremely light (a shallow sandy loam with 40-60% stone content) through to poorly drained silty clay loam (Table 1).

For the purpose of calculation, SPASMO requires a functional form for the soil's water retention curve. This was achieved by fitting each set of water retention data (i.e. the total porosity (TP), field capacity (FC), wilting point (WP) points shown in Figure 3) to the van Genuchten (1980). FC is given by the water content at a potential of -10 kPa; WP is defined by the water content at a potential of -1500 kPa. The refill point for irrigation is typically at a potential of about –100 kPa.

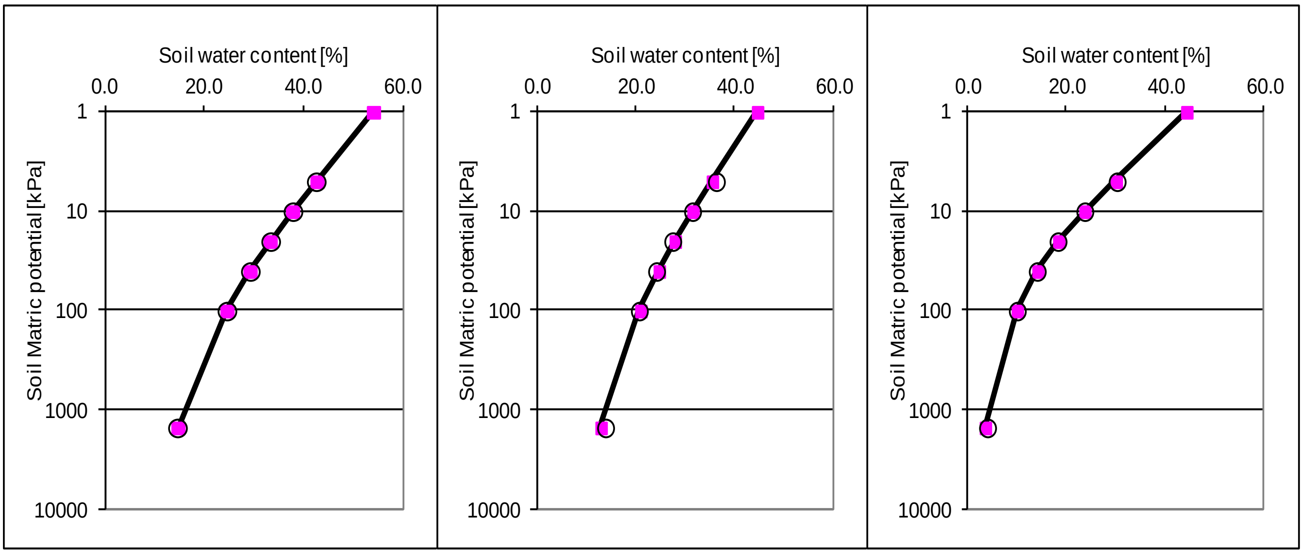


Figure 3. Water retention properties for the Ruataniwha series soil: 'left panel' is the top 20 cm of loam, 'middle panel' is 40 cm of silt loam, and 'right panel' is 40 cm of sandy loam. The van Genuchten (1980) model was fitted to each water retention curve.

Model farm scenarios and land uses

AgResearch was assigned the task to spatially map and define 'current land use' and land use change scenarios that would be feasible for irrigable land on the Ruataniwha Plains based on the nine 'model farms' (Table 2) taken from the Macfarlane report (2011). The water and nutrient loadings for each of the enterprises for each of the model farms was calculated for each of the soils and microclimates found within the irrigation zones. The end result was a table of monthly outputs (spanning 480 months) from the 4350 model runs. AgResearch's GIS modelling platform was then used to interrogate these look-up tables and average the model outputs across the enterprises that make up each model farm.

Table 2. Model farm types and stocking rates (SU = stock unit) identified in the McFarlane et al. (2011) report.

Scenario No.	Model Farm Type	Stocking Rate
1	Sheep and beef breeding and finishing	10-11 SU
2	Mixed livestock with dairy support	10-11 SU
3	Finishing farms	10-11 SU
4	Intensive mixed livestock	5SU + cropping
5	Arable with a range of crops	5SU + cropping
6	Dairy heavy soils	21 SU
7	Dairy light soils	23 SU
8	Pipfruit	-
9	Viticulture	-

For the purpose of modelling, each farm type is specified by a production target (e.g. dairy is represented by kg of milk solids per ha, sheep and beef are represented by live weight gains, and arable and horticulture are represented by kg of product per hectare). For each model run, the input parameters for SPASMO were 'set' to achieve the expected yields and production volumes that were specified in the Macfarlane et al. (2011) report.

Initial model runs compared the enterprises in the pre- and post-storage model farm types described in the Macfarlane's (2011) prefeasibility study of the proposed irrigation scheme. The timing and amount of irrigation was based on best practice (matching irrigation to crop needs), with advice from a panel of expert scientists. The fertilizer regimes for each farm were set to match the demands for each crop, based on the nutrient requirements to achieve a healthy, actively-growing crop. We have chosen to assume the same annual inputs of N and P fertilizer as specified in the Macfarlane et al. (2011) report. Then expert opinion was sought to specify the timings for each fertilizer application for the pastoral simulations, in order to follow a maintenance schedule proposed by AgResearch.

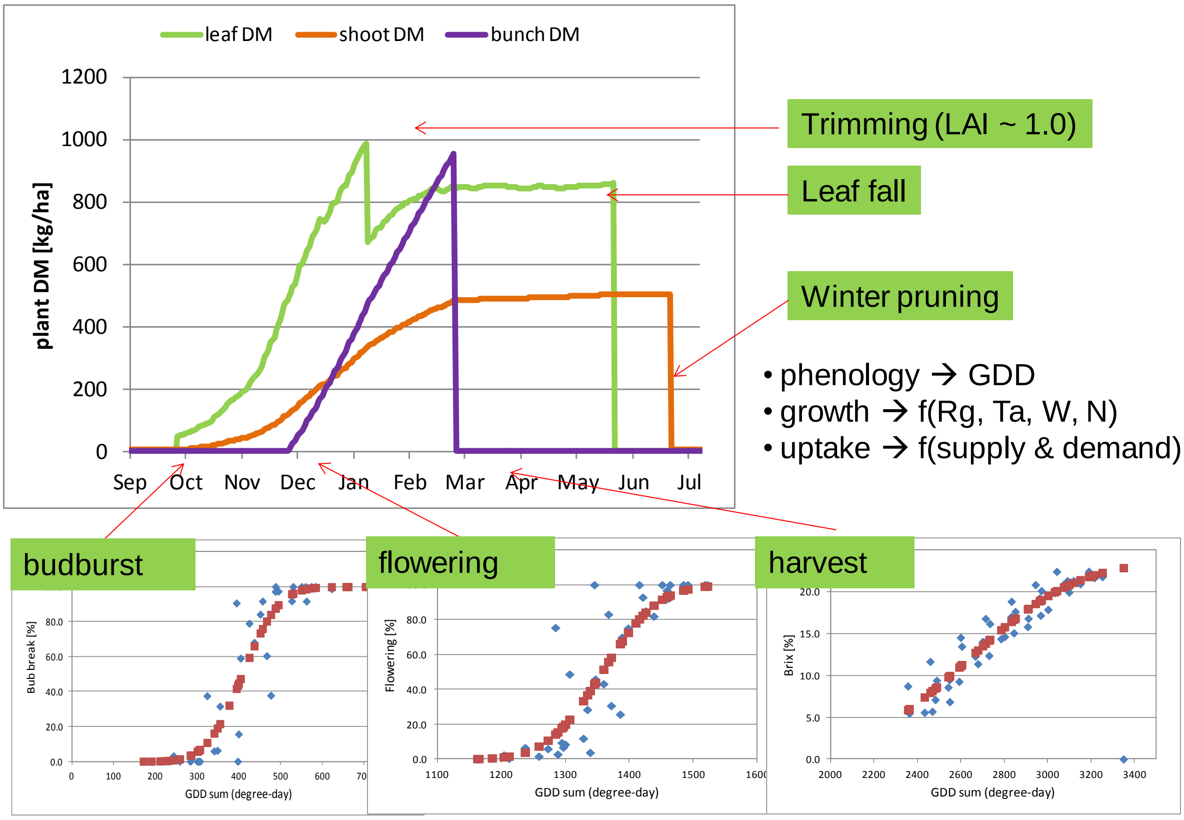
Specific details for each farm scenario can be found in the Macfarlane et al. (2011) report. In all cases, SPASMO has been parameterized to match, as closely as possible, each of the nine model farm types listed in Table 2. Salient details for some of those farm types are presented below in order to convey the degree of detail involved in the SPASMO simulations.

Horticulture – apples and wine grapes

A set of crop-dependent parameters have been used to simulate the seasonal development of dry matter (DM) going into the leaves, shoots, roots and fruits. The plant growth component of the model is similar to that of Eckersten & Jansson (1991), where daily biomass production is modelled using a potential production rate (kg m^2 d^{-1}) that depends on the amount of light intercepted by the green leaves. Nitrogen accumulation to the various plant organs depends on the leaf nitrogen content and the potential supply of N from the root-zone soil. If water and nutrients are limiting, plant growth and N-uptake are curtailed. Model parameters for crop growth and N-uptake were selected here to match typical values for leaf area index, fruit yield and the nitrogen contents of the various plant parts.

The crop model is very dynamic and responsive to changes in the climate as well as the water and nutrient status of the root-zone soil (Green et al. 2006). Some crop parameters are needed to account for physiological events (e.g. budburst, flowering, fruit maturity, leaf fall), while other parameters deal with aspects of management (e.g. harvest, summer/winter pruning, irrigation, nitrogen fertilization). An example of model outputs for the DM allocation in grapes is shown in Figure 4.

For simplicity it is assumed that all crop material (i.e. bunches of mature grapes or numbers of mature apples) would be harvested and the corresponding dry matter, along with its N and P content, would be removed from the vineyard or orchard. Following leaf fall and pruning events, all plant biomass is assumed to be mulched (i.e. mowed up) and returned to a surface layer, where it slowly decomposes, releasing dissolved organic matter (i.e. both carbon, nitrogen and phosphorous) to the soil profile. Litter decomposition is a very important process for returning nutrients and carbon to the soil system. In terms of potential nitrate leaching, our own measurements from apple orchards near Hastings have found annual leaching loss of ~10 kg N/ha (Figure 5). We report these values here simply to establish how much N leaches from apples.



- phenology → GDD
- growth → f(Rg, Ta, W, N)
- uptake → f(supply & demand)

Figure 4. SPASMO (Soil Plant Atmosphere System Model) includes components for crop phenology (i.e. budburst, flowering and harvest) that help establish dry-matter allocation (DM), and irrigation management of the grapevines. The bottom panels show data sourced from regional grape trials in Marlborough (blue symbols) compared against predictions from SPASMO (red symbols). The phenology models are based on growing degree days (GDD). The crop growth model is based on daily values of global radiation (R_g), leaf area index (LAI), air temperature (Ta), soil water (W) and soil nitrogen (N) content. The phenology data were provided by Alistair Hall (PFR, pers. comm.).

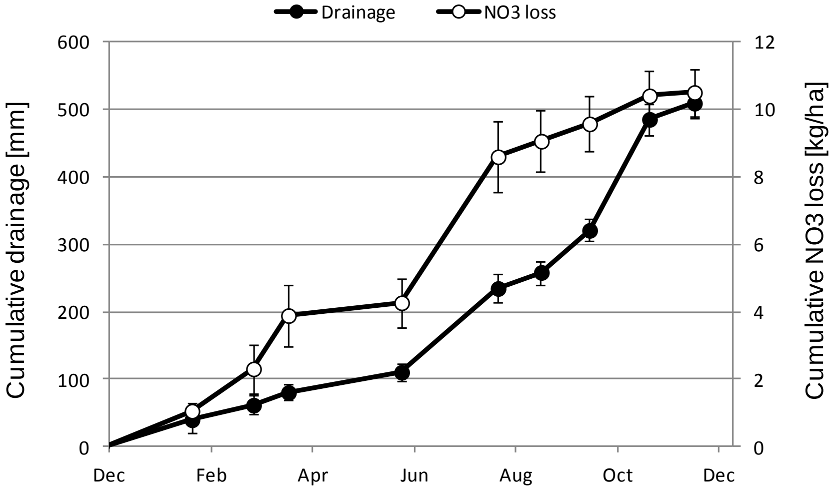


Figure 5. Drainage and nitrate leaching under an apple orchard in the Hawke's Bay, as measured with six passive-wick drainage meters (S Green, unpublished).

Horticulture – Vegetables and arable crops

The growth and development of a sequence of arable crops including oats, lucerne, barley, potatoes, wheat, maize, vining peas and forage brassicas are modelled using the same sets of allocation equations as for the tree and vine crops, but with parameter values adjusted to the expected yields and nutrient uptakes for each crop. These parameter values are deduced from data reported in Thorup-Kristenson (2006) and Karam et al. (2002), the modelling paper of Tei et al. (1996), the guidelines of the forage brassica group (de Ruiter et al. 2009), and fertilizer guidelines either reported on the internet (HortPlus™ and the Yates Growers' Guides) or deduced from the Macfarlane et al. (2011) report. An example showing the dynamics of crop growth and nitrogen uptake for dryland lucerne is shown in Figure 6, and an example showing the dynamics of crop growth and nutrient uptake for maize silage is shown in Figure 7.

SPASMO accommodates multiple crop rotations in a single calendar year, with all crop residues being ploughed back after harvest. The modelling framework accounts for the release and movement of dissolved organic matter (i.e. dissolved organic-C, organic-N and organic-P) originating from the breakdown of any plant material left after each crop harvest. This decomposition is important, since it alters the soil C:N ratio and this has an impact on rates of nitrogen-mineralization. The modelling procedure used by SPASMO to simulate nitrogen mineralization has been previously verified against data from laboratory incubation studies (Figure 8).

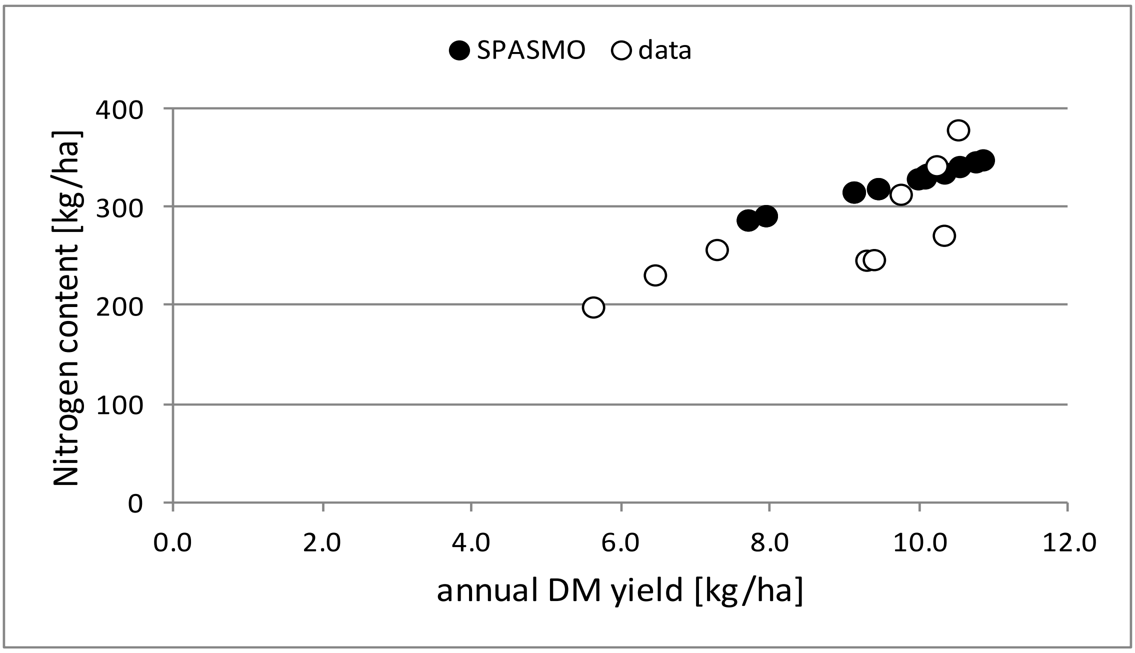


Figure 6. The relationship between annual dry-matter (DM) production and total nitrogen uptake by dryland lucerne. The open markers represent data from Rothamsted, UK (Bell & Nutman 1971) and the filled markers are calculations using SPASMO (long-term averages) for climate station No. 27371. Note: Lucerne is a legume and so no nitrogen fertilizer was applied, yet the plants still accumulated some 290-350 kg N/ha each year.

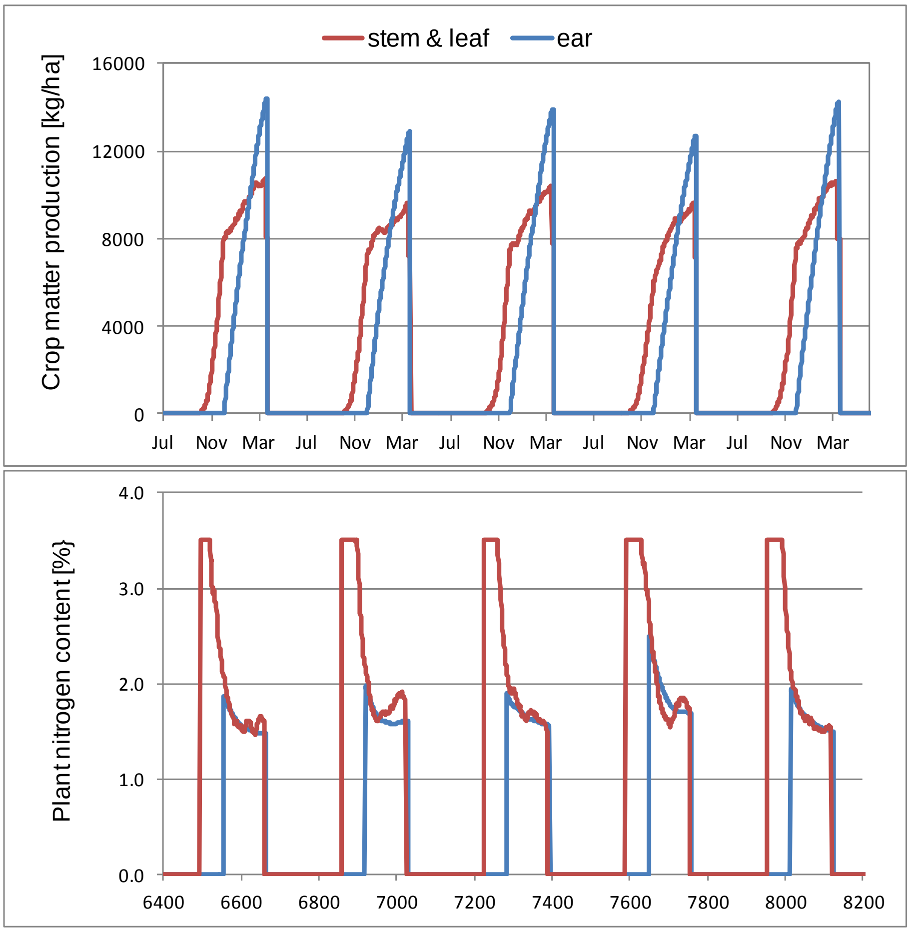


Figure 7. Seasonal dynamics of dry matter (top panel) and the corresponding nitrogen content (bottom panel) of the above-ground biomass of maize, as modelled by SPASMO. These simulations assume 140 kg/ha of nitrogen fertilizer is applied in the spring time. The expected production for maize silage (i.e. above-ground total for stem + leaf + ear) in central Hawke's Bay is around 22 T/ha (www.pioneer.co.nz).

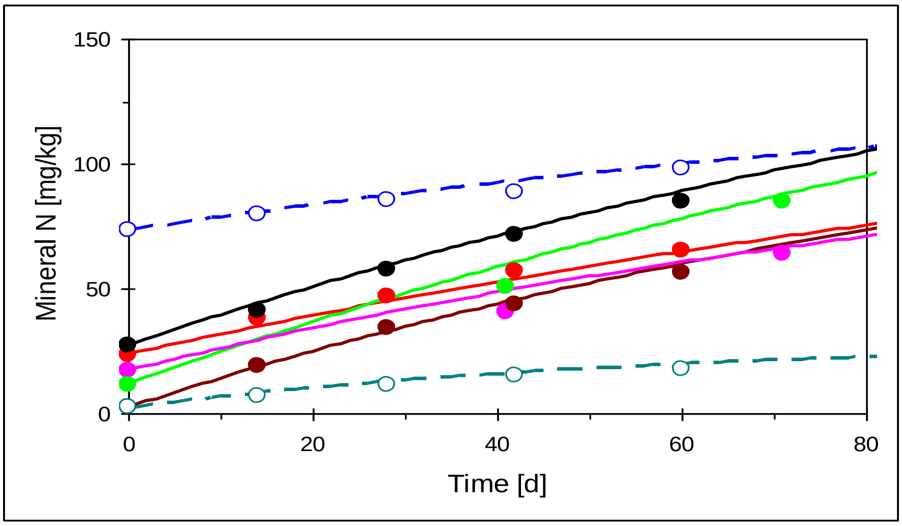


Figure 8. Nitrogen mineralization rates in a range of New Zealand soils as measured during laboratory incubation studies under controlled temperature and moisture regimes. The symbols represent data and the lines are modelled with SPASMO using first-order release rates (S Green and M Deurer, unpublished). Soil labile carbon and nitrogen and the C:N ratio of the bulk soil are important drivers of the mineralization process (Kim et al. 2011).

Pasture simulations.

The pasture growth component of SPASMO is described in Rosen et al. (2004). For the present study, values of the model parameters were set to match results from our field experiments from an irrigated dairy farm at Tikokino (Green et al. 2000), which is within the proposed irrigation zone. The pasture growth component appears to be ‘well-tuned’ to local growing conditions (Figure 9).

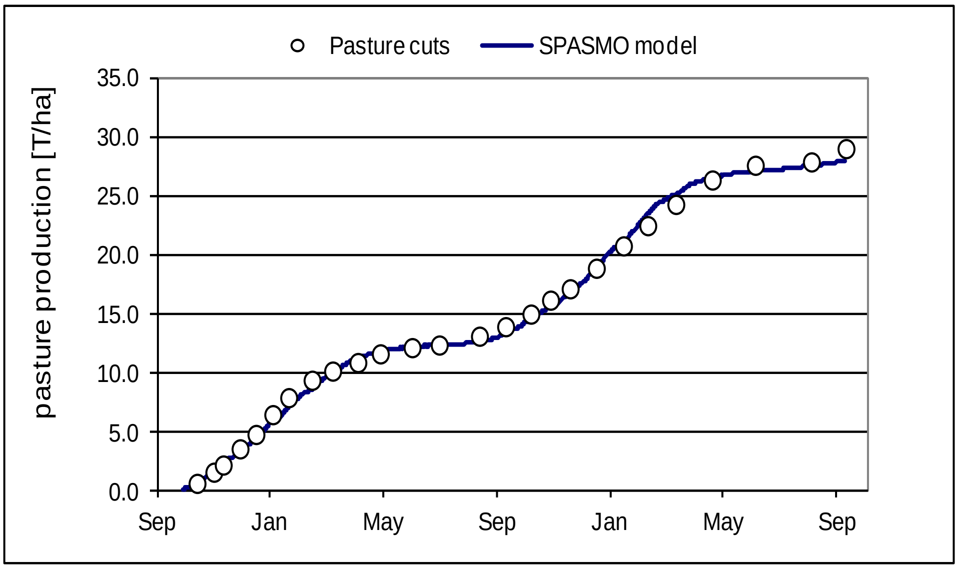


Figure 9. The cumulative pasture production from an irrigated dairy farm near Tikokino as measured from ‘pasture cages’ on the farm (symbol) and as modelled using SPASMO (see Green et al. 2000 for details).

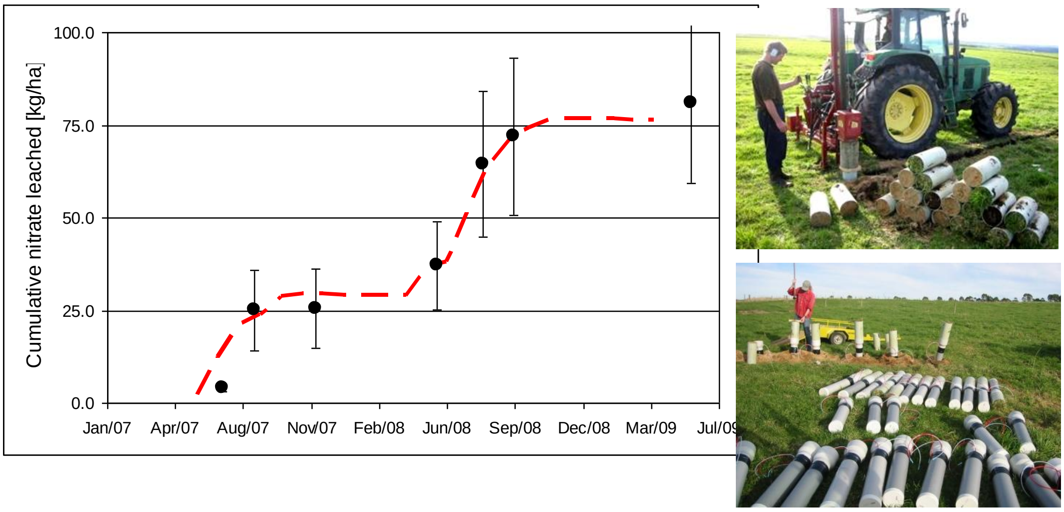


Figure 10. Measured (symbol) and modelled nitrate leaching from a dairy farm near Taupo. A total of 45 drainage lysimeters were installed in three paddocks, and they are being monitored at 1 to 2-month intervals to assess the drainage of water and the leaching of nitrate and ammonium (Green 2009, unpublished).

We have no data to check our calculations of leaching under pastoral farms in the Hawke's Bay. However in previous work, we have compared SPASMO model outputs against nitrate leaching data from a dryland dairy farm near Taupo. In that case, we found a very good agreement between model outputs and our observations obtained using passive-wick drainage lysimeters (Figure 10). Thus, we consider the leaching component of the model to be realistic for a grazed-pasture system. There is a wide scatter in the leaching data, and that is attributed to spatial variability associated with the random deposition of 'urine patches' on the fluxmeters. In general there is good agreement in both the temporal pattern and the magnitude of the nitrate fluxes.

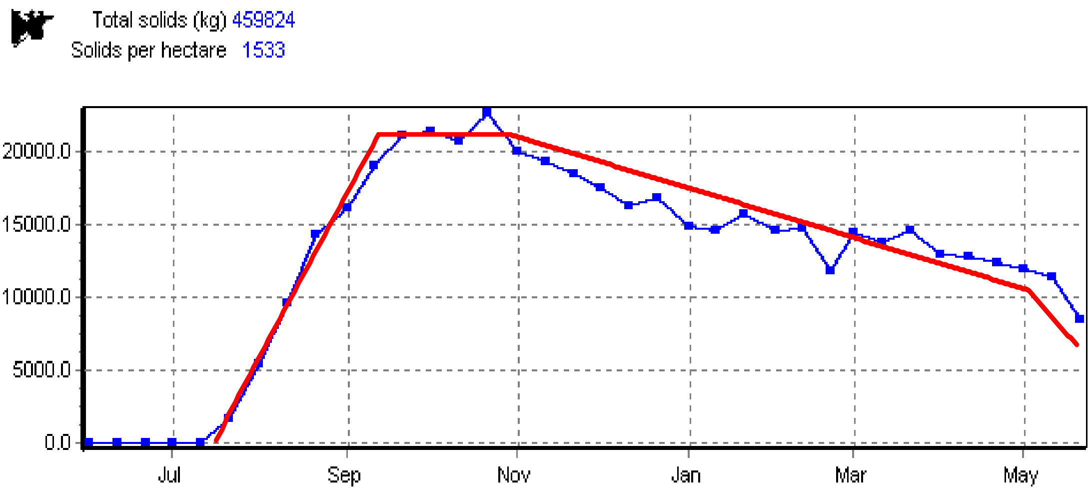


Figure 11. Milk production profile for model dairy farm as described in the Macfarlane et al. (2011) report (blue line). The red line shows the same farm modelled using SPASMO.

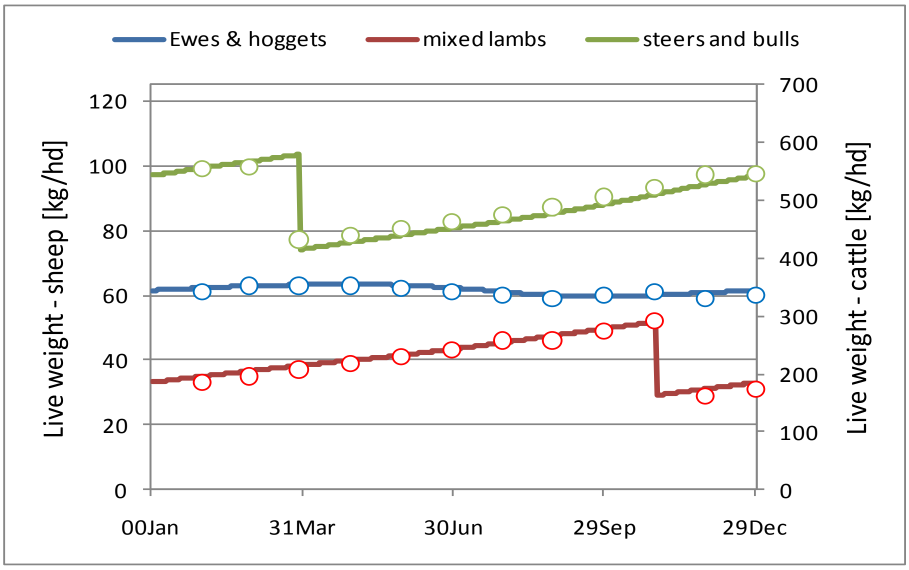


Figure 12. Animal production targets for a sheep and beef enterprise (scenario 1a). Symbols represent production targets from the Macfarlane et al. (2011) report that were calculated using FARMMAX™ and the lines represent animal growth calculated using SPASMO.

For each pastoral system, stocking rates of our model farms were matched to those described in the Macfarlane et al. (2011) report. SPASMO outputs were then cross-checked against calculations of animal feed intake predicted by farm consultants using AgResearch's FARMMAX™ model (Figures 11 and 12). Thus we are also confident that the animal component of the farm model approximately matches expected farm production rates.

Results and Discussion

The task here was to simulate an irrigation demand and potential nitrate leaching from a range of farming enterprises. Each simulation involved a unique combination of soil+climate+enterprise type. Some model farm types (e.g. arable with a range of crops) required us to generate model runs for more than 10 different parcels of land on each farm unit. Thus, many hours were spent 'cranking the handle'. Initial model outputs were straightforward and involved a calculation of the irrigation demands for pasture (Figure 13). Those model outputs were used to assist in refining the size of the storage dam and specifying the infrastructure to deliver water where and when it is needed. That work is in progress with Tonkin and Taylor.

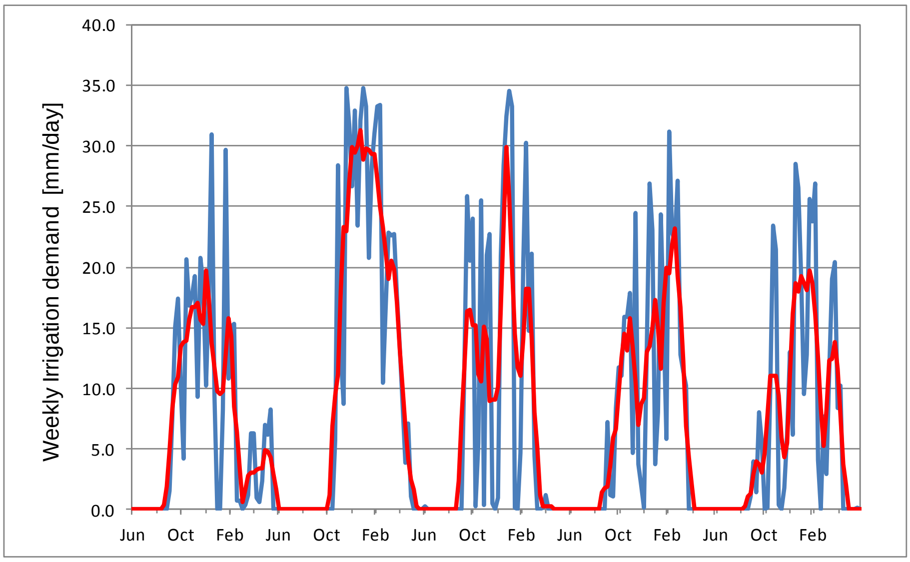


Figure 13. SPASMO was used to calculate the average (weekly) irrigation demand for pasture growing on the Ruataniwha Plains. This average considers 52 soil types across the four irrigation zones (total area ~32000 ha). The blue line is the model output each week and the red line represents a 3-week running mean. Year to year variation is a reflection of the variable and erratic nature of summer rainfall.

Model outputs for the annual losses of nitrate-nitrogen for a range of model farm types are presented in Figure 14. SPASMO calculates between 3-11 kg N/ha is lost from grape vineyards and between 6-15 kg N/ha is lost from apples, on average. The latter estimates for apples are in accordance with our data from Hastings (cf. Figs 14b and Fig. 5). Some soils like the Tukituki and Argyl gravelly sands, have very low water and nutrient holding capacities and are probably better suited to grapes rather than the other farming enterprises.

The small amounts of N leached under apples and grape production reflects the small amounts of N used in the production of both these crops and the adoptation of deficit irrigation regimes.

In general, the irrigated pastoral systems (irrigated sheep and beef finishing, and irrigated dairy) tend to leach more N than the irrigated tree and vine crops. This is due to a combination of factors. Associated with irrigation is the use of N-fertilizer in the irrigated dairy operation, further increasing forage and milk production. While direct N leaching losses from N-fertiliser application can occur, it is the impact that the added N-fertiliser has on animal returns of urine (which is highly mobile) through the increased amounts of forage grown, that leads to increased N leaching losses. Irrigation increases the risk of N leaching losses occurring in season. It should be noted that our model outputs for pastoral farming represent the scenario with all animals being wintered on-farm, and with no mitigation options (e.g. feed pads, inhibitors, wintering off) being considered. In that case, we calculate large losses on the shallow stony soils (e.g. the outlier on Figure 14c), which could be reduced in practice mitigation practices. AgResearch, we are currently working through a range of mitigation options, in their modelling of the land use impacts, to identify options that will reduce the potential losses of N and P.

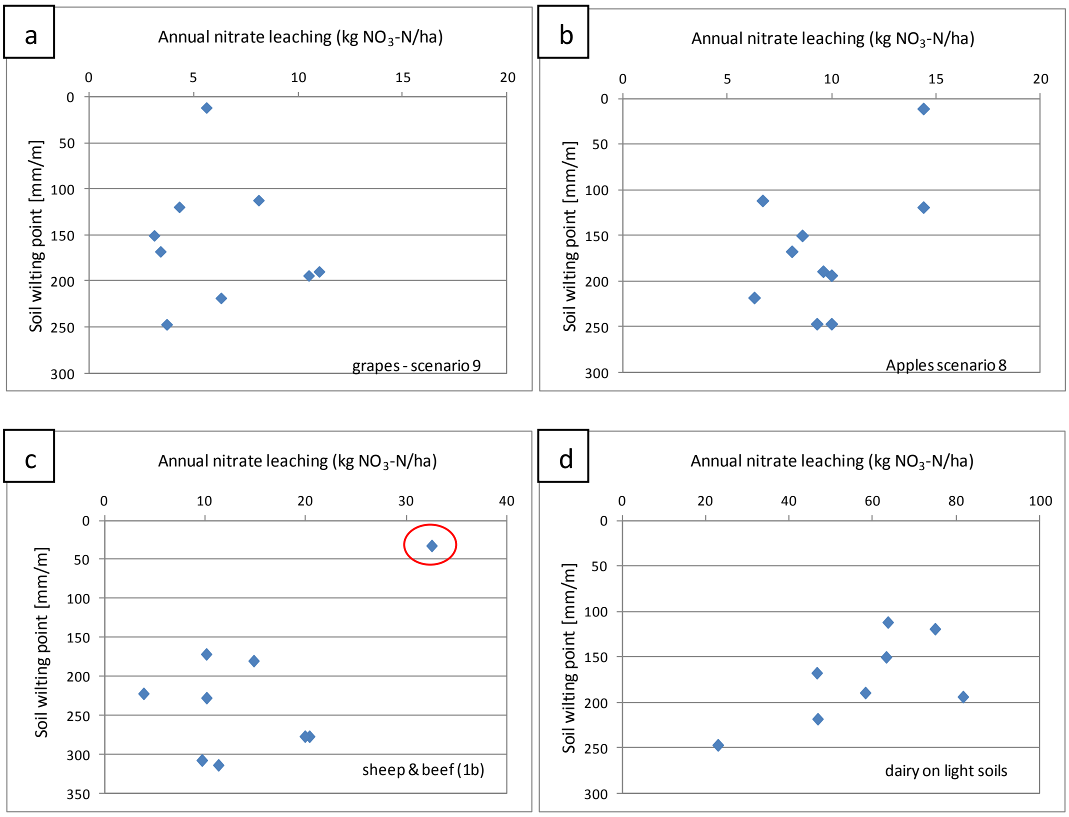


Figure 14. Model outputs of nitrate leaching under a range of model farms: (a) wine grapes, (b) apples, (c) intensive sheep and beef, (d) dairy on light soils (wintered on-farm). The effect of soil type is expressed via the soil's wilting point (WP). Some of the very stony soils (e.g. the outlier in scenario (c)) have a very low WP (Table 1).

Eventually, the modelling team (AgResearch, NIWA and PFR) will be simulating the impacts of five alternative land-use scenarios. These will be the pre-storage scenario that represents the current mix of land uses, plus four future land-use scenarios. Presently, we have only just completed our modelling of the existing land-use scenarios plus one half of the 'fully implemented' mix of post-storage land uses. From that modelling, we have already generated more than 2 GB of model outputs across the full complement of about 18,000 different combinations of climate & soil & farm type. That represents a very large data set.

Key model outputs from this study have now been passed to NIWA to model the effects of land use intensification on water quality in the Tukituki and Waipawa Rivers. The aim of the current research project was to first model the dynamics of land use on the Ruataniwha Plains and the influence this has on surface and ground water quality, then to use this model to assess the potential effects of land use change on surface and groundwater quality as a result of irrigating from stored water, and finally to develop and test workable farm management and other mitigation opportunities to offset any defined potential adverse effects associated with realistic land use change scenarios modelled using the NIWA land use / water quality model.

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