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A nitrogen balance model for environmental accountability in cropping systems

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In New Zealand and worldwide, growers are increasingly being required to demonstrate that their nutrient management does not have adverse effects on the environment. Since routine direct measurements of nitrogen (N) losses at an appropriate scale are currently unfeasible, a modelling tool that can be used to assess losses, both actual and potential, from farming systems is therefore needed. We present the upgraded N balance module for cropping systems (OVCrop) developed to be incorporated into the OVERSEER[®] Nutrient Budgets model. It presents an easy-to-use interface, requiring few but meaningful inputs, with the minimum flexibility needed to describe management of real farming systems. Following the developmental guidelines of OVERSEER[®] Nutrient Budget, OVCrop is designed to provide the long-term annual average of N leaching from any user-defined cropping rotation. OVCrop has been parameterized based on process-based model simulations for typical farm systems and environments of New Zealand. The intended use of the OVCrop is to help on-farm nutrient management and to demonstrate future compliance to N leaching regulations. OVCrop is a robust tool, simple enough to be used by people with a low to medium level of expertise, such as farmers and regional councils.

Keywords: N leaching; nutrient budget model; model development; model evaluation

Introduction

The need for a nitrogen balance tool

Agriculture is an important sector of New Zealand's economy, contributing to about 50% of New Zealand's export earnings (Statistics New Zealand 2007). Its competitiveness in the world market has been maintained by significant gains in productivity, mostly driven by land-use intensification. This intensification has been sustained by practices such as the use of fertilizers and irrigation, which also increases the potential for nutrient losses. Limiting such losses is highly desirable as they represent an economic

cost to growers and may also cause environmental damage.

The impact of agricultural activities on the environment is a matter of increasing public concern in New Zealand and worldwide (Kroeze et al. 2003; Oenema et al. 2003; Parliamentary Commissioner for the Environment 2004; Shepherd & Chambers 2007; Skinner 2007). Land-use regulation in New Zealand is largely output driven, that is, the legislations focuses on the effects of a land activity rather than on the impact of nutrient inputs to that land. As a result of these regulations, growers are increasingly being required to demonstrate that their

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management does not have adverse effects on the environment (Öborn et al. 2003; Dragten & Thorrold 2005; Agricultural Nitrogen Managers Group 2006). Few regional councils in New Zealand are proposing guidelines with strict nutrient management practices, with limits on nitrogen (N) concentration in the leachate under farming systems. These initiatives, and similar others around the world, raise an important issue: how to assess the effects of current management as well as alternatives in order to demonstrate compliance to such guidelines.

There is a need therefore for tools that can be used to assess nutrient losses, both actual and potential, from farming systems. Routine direct measurements of N losses at an appropriate scale are currently not feasible. They are time consuming, costly, and present high variability at farm scale. It is not surprising therefore, that the use of computer models for assessing and monitoring nutrient losses is gaining recognition as a more suitable alternative to measurements (Ledgard et al. 2004; Veihe et al. 2006; Langeveld et al. 2007; Monaghan et al. 2007; Delgado et al. 2008).

Current tools and necessary developments

Any tool required for monitoring and compliance should be simple enough to be used by people with a low to medium level of expertise, such as farmers and regional councils, and should be operated using easily gathered input data. The most widely accepted farm-scale nutrient budgeting tool developed for New Zealand conditions is the OVERSEER[®] Nutrient Budgets model¹ (Ledgard et al. 1999; Wheeler et al. 2003, 2006). The OVERSEER[®] Nutrient Budgets model (hereafter referred to as 'Overseer') has been widely used in the pastoral sector for predicting the N balance of farming systems. Overseer is built using quasi-empirical relationships and internal databases based on research conducted in New Zealand. The model estimates the nutrient inputs and outputs at paddock or farm scale and presents these as a nutrient budget. The model assumes that best management practices are followed and produces estimates of long-term averages on an annual basis. This approach allows a

relatively simple-to-use interface with inputs and outputs familiar to most end-users (farmers, consultants, regional councils, etc.). The Overseer model was developed initially to aid with nutrient management in pastoral farms from a production perspective (Ledgard et al. 1999). Later it has been updated and used for improving nutrient-use efficiency, evaluating some mitigation options, and estimating nutrient outputs to the environment (Ledgard et al. 2001; Wheeler et al. 2006, 2009). Although Overseer has horticulture and cropping modules, they have not been as widely tested or updated as frequently as the pastoral module.

To estimate fairly the nutrient balance of cropping systems, a sub-annual time-step has to be used to capture adequately the effect of the various cultural and management events. Cropping systems are dynamic, with dramatic disparity in both the timing and extent of crop status (soil cover, root depth, N uptake pattern) and management events (tillage, irrigation and fertilizer) over the year. This system also involves multiple crops within a rotation. These factors may vary substantially between paddocks and years, depending on the rotation and management applied. The timing of fertilizer and irrigation applications in relation to the plant demand has an important influence on the nutrient balance of cropping systems, and therefore estimation of nutrient balance on an annual basis may not fairly capture these timing effects. A review on the current Overseer crop and horticulture modules and the needs of regional councils and the industry has been conducted recently (Agricultural Nitrogen Managers Group 2006). It was concluded that the existing Overseer modules were neither robust nor easy enough to use to be adopted for monitoring N losses on a scale required for compliance assessment for arable farms.

The need for a major upgrade of the mechanism of these modules and their interface was identified. While it was clear that a more detailed mechanism was necessary to capture paddock specific variation, this had to be balanced with the need to keep the model simple so it is easy to set up and use. It was expected that simplicity would not compromise the accuracy of the tool, as simple quasi-empirical models have been shown to be as good as process-based models

at predicting medium to large-scale phenomena (Addiscott 1995; Watson & Atkinson 1999; Schlecht & Hiernaux 2005; Adams 2007).

Here we present the upgraded N balance module for cropping systems that has been developed to be incorporated in the Overseer model. We describe the model outline (herein referred to as the upgraded Overseer crop model, OVCrop) and the approaches taken to quantify and test its mechanisms and parameters.

Approach used for development and validation

One of the reasons that the cropping module for Overseer has not been upgraded as frequently as the pastoral module is the lack of appropriate long-term data to quantify the nutrient balance under cropping systems. The approach decided upon for this upgrade was to use results from detailed process-based models to determine simplified empirical functions for the Overseer modules. Process-based models, such as LUCI (land use change and intensification) (Jamieson et al. 2003a; Li et al. 2007; Zyskowski et al. 2007a) and SPASMO (Green et al. 2004; Rosen et al. 2005), have been developed and validated against short-term experimental data in New Zealand. A relatively high number of input data and parameters are required when using these models; also a high level of user expertise is needed to ensure that reliable results are produced. Typically, process-based models are used in research and consulting and not suited for widespread use in compliance monitoring. However, the use of results from validated process-based models has been advocated as surrogate for the lack of measured data when developing or testing simpler models (Young et al. 1996; Khaither & Erechtkoukova 2007). For the development of OVCrop, LUCI framework model simulations were used to devise simple relationships and to estimate their parameters. This is a means of extrapolating from basic principles of plant and soil processes and short-term validations to produce synthetic long-term average data.

The LUCI framework model

LUCI is a model framework for simulating plant growth and soil processes, such as water and N balances, at paddock scale with different land uses and management systems (Jamieson et al. 2006a; Zyskowski et al. 2007a). It is a daily time-step process-based model framework built combining a series of crop and soil models developed by Plant and Food Research (Jamieson et al. 1998, 2006b; Zyskowski et al. 2004; Li et al. 2006, 2007). Several of these models have been extensively used for tactical irrigation and fertilizer management. The integration of these models into the LUCI framework allows the simulation of crop rotations and the analysis of the effects of land-use changes over time.

The crop calculators and therefore LUCI were built based on sound knowledge about the various processes involved in plant growth and the movement of water and solutes in the soil. These models have been tested (e.g. Jamieson et al. 1998, 2003a, 2003b; Armour et al. 2002; Li et al. 2006) and successfully applied in a range of studies (Snow et al. 2007a, 2007b; Zyskowski et al. 2007b).

Model description

Overview

The OVCrop was designed to provide reliable estimates of long-term annual N leaching from any user-specified cropping rotation. As the intended use of the OVCrop is to demonstrate future compliance to N leaching regulations, long-term average weather data and databases with generalized plant and soil parameters are used to set up the simulations. Leaching was defined as the N percolating below 1.5 m depth, the maximum root depth of most crops grown in New Zealand. The soil is assumed to be homogeneous down to a gravel layer. Calculations are done on a monthly basis and comprise two years. The first year is set up to represent the management prior to the year being assessed. Running the calculations for the previous year gives an estimate of the soil status N for the start of the assessed year, reducing the need for soil measurements. It also accounts for the effect of residuals from

previous crops. Monthly calculations are considered short enough to capture the effects of management when reporting on an annual time-step. Only the annual amount of N leaching corresponding to the second year is reported by OVCrop.

The information supplied via the user interface includes the farm location, which determines, from internally stored databases, the monthly averages of rainfall, potential evapotranspiration and air temperature. These can be modified by the user. The user also specifies the appropriate soil type and the depth to the gravel layer. These are linked to a database of parameters that define the soil water storage capacity, derived from the NZ national soils database (Wilde 2003), and the soil specific parameters used to predict drainage and leaching. Land-use history is specified as a simple description of the proportion of the 10 years prior to the assessment that the paddock has been under pastoral use (τ_{YIP}). Finally, the rotation description (crop type, sowing month, tillage type, residue treatment, irrigation, and fertilization schedules) must be given. The key input specified in the crop rotation is the expected yield which is used to calculate crop N removal and N returns as crop residual, including roots. The user inputs, provided via the interface, are linked to the internal parameters that provide the basis for crop and soil calculations.

The OVCrop has two core procedures, one for computing the water balance and providing estimates of drainage, and the other for evaluating the N balance and the amount of leaching (Fig. 1). The main formulae are presented hereafter, full description are to be incorporated in the model's documentation.

Water balance

The soil water balance, for a given month m , is described by Equation 1:

$$W_{SOIL(m)} = W_{SOIL(m-1)} + (W_{IRRIG(m)} + W_{RAIN(m)} - (W_{EVAPO(m)} + W_{TRANSP(m)} + W_{DRAIN(m)})) \quad (1)$$

where W_{SOIL} is the plant available water stored in the soil profile (difference between wilting point and field capacity); W_{IRRIG} and W_{RAIN} are the water inputs via irrigation and rainfall; W_{EVAPO} and W_{TRANSP} are the losses via evaporation and plant transpiration; and W_{DRAIN} is the drainage amount.

The monthly irrigation amounts can be computed based on an irrigation method chosen or can be given directly provided by the user. For rainfall, the annual average is a user input while the monthly distribution is obtained from an internal database linked to the selected location and user inputs describing seasonality patterns. Evaporation and transpiration are taken as the minimum between the water demand and the water supply. The water demand is given by the potential evapotranspiration (E_{TP}) and is partitioned between evaporation and transpiration in relation to crop cover (k_{COVER}). The water supply in any month is given by the sum of W_{IRRIG} and W_{RAIN} plus, for transpiration, the available water in the root zone (W_{SOIL_RZ}), which is a function of soil type, stoniness and crop age (root depth):

$$W_{EVAPO(m)} = \min(E_{TP(m)}k_{EVAPO(m)}, W_{IRRIG(m)} + W_{RAIN(m)})(1 - k_{COVER(c,m)}) \quad (2)$$

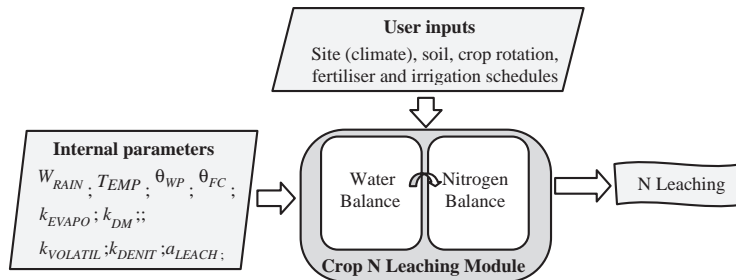


Fig. 1 Flowchart of the proposed OVCrop module for N leaching estimation.

$$W_{TRANSP(m)} = \min(k_{COVER(c,m)}E_{TP(m)}, W_{SOIL_RZ(m-1)} + k_{COVER(c,m)}(W_{IRRIG(m)} + W_{RAIN(m)})) \quad (3)$$

The empirical factor (k_{EVAPO}) was included to account for reduction in evaporation as the soil surface dries out. Details of the derivation of k_{EVAPO} are given below. It is also considered that soil moisture does not go below the wilting point. In both Equations 2 and 3, k_{COVER} is the plant-cover coefficient which increases from 0, with bare soil, to 1, when plants have grown a fully closed canopy. The relationship devised to describe the temporal pattern of k_{COVER} for different crops is given in the results section.

The amount of water lost via drainage is any volume above the soil storage at field capacity (W_{FC}):

$$W_{DRAIN(m)} = \max(W_{SOIL(m-1)} + W_{IRRIG(m)} + W_{RAIN(m)} - W_{EVAPO(m)} - W_{TRANSP(m)} - W_{FC}, 0) \quad (4)$$

The values of W_{FC} are computed for each soil type based on its characteristics (depth to gravels and texture).

Nitrogen balance

The balance of mineral N in the soil is described, for each month, m , by Equation 5:

$$\begin{aligned} N_{MIN(m)} = & N_{MIN(m-1)} + N_{SHORTAGE(m)} \\ & - N_{SHORTAGE(m-1)} \\ & + (N_{FERT(m)} + N_{RAIN(m)} + N_{IRRIG(m)} \\ & + N_{SOM(m)} + N_{RESIDUE(m)}) \\ & - (N_{VOLATIL(m)} + N_{DENIT(m)} \\ & + N_{UPTAKE(m)} + N_{LEACH(m)}) \end{aligned} \quad (5)$$

where N_{MIN} is the amount of mineral N in the whole soil profile; N_{FERT} , N_{RAIN} and N_{IRRIG} are inputs via fertilizer application, from rainfall and the irrigation water; N_{SOM} and $N_{RESIDUE}$ are the amounts of N mineralized from the soil organic matter and the residues of the previous crops; $N_{VOLATIL}$ and N_{DENIT} are gaseous losses via volatilization and denitrification; N_{UPTAKE} is the amount of N taken up by

plants; N_{LEACH} is the N lost via leaching; and $N_{SHORTAGE}$ is a term used to ensure mass balance and is used to help alert the user to infeasible or unlikely combinations of inputs.

The fertilizer amount is given by the user. The amount of fertilizer N volatilized is then estimated from a relationship based on a summary of data from New Zealand which includes monthly temperature and rainfall, and soil and cover terms (Woodward 2007). The N inputs via rainfall and irrigation are computed based on the water amounts and their N concentrations, set as internal parameters. Denitrification is estimated as a function of the soil water content and temperature (Eq. 6):

$$N_{DENIT} = N_{MIN(m-1)}k_{DENIT}f_{TEMP} \max\left(\frac{f_{SWC} - b_{DENIT}}{1 - b_{DENIT}}, 0\right) \quad (6)$$

where k_{DENIT} has a value of 0.05, assuming a maximum of 5% of mineral N is lost to denitrification per month when the soil is at field capacity and 20°C. f_{SWC} is the ratio between the soil water amount in the current month and the potential water storage at field capacity. A simplified description of denitrification is used assuming it decreases linearly as soil dries out, reaching zero when the soil water content equals 80% of the holding capacity, so b_{DENIT} has a value of 0.8. f_{TEMP} is a temperature factor (Fig. 2a) taken from the literature (Aslyng & Hansen 1982; Addiscott 1983), but the function was scaled to unity at 20°C for use in the calculation of denitrification (Fig. 2a).

The mineralization from the soil organic matter (N_{SOM}) is calculated from the amount of soil organic N (N_{ORG}) following a first order decomposition function, and is influenced by soil water content and temperature (Equation 7):

$$N_{SOM(m)} = N_{ORG}f_{SOM(m)}f_{SWC(m)}f_{TEMP(m)} \quad (7)$$

N_{ORG} is estimated as a linear function in relation to of the proportion of time in the past 10 years the field was under pasture (with intercept of 4000 kg ha⁻¹ and slope of 100 kg ha⁻¹ yr⁻¹). f_{SOM} is related to τ_{Yip} to capture the fact that resident organic matter degrades at a slower rate for fields that have been under cultivation for an

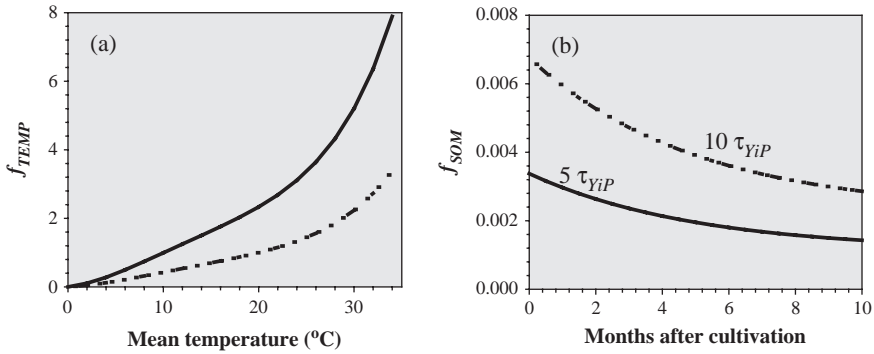


Fig. 2 (a) Temperature factor (f_{TEMP}) for a range of mean monthly temperatures used in OVCrop. Dashed line is the scaled f_{TEMP} used in the calculation of denitrification. (b) The soil organic matter mineralization factor (f_{SOM}) over time for two values of years in pasture (τ_{YIP}).

extended period. f_{SOM} is also a function of the time since the last cultivation event, thus representing the flush of mineralization that occurs just after the cultivation (Fig. 2b). The influence of τ_{YIP} on N_{ORG} and f_{SOM} was determined by analysis of organic N content and mineralization rates in a long-term trial monitoring soil changes following conversion from pasture to cultivated land use (D. Curtin and M. Beare, Plant and Food Research, Lincoln, unpublished data).

The crop N demand is calculated from the yield specified by the user. Parameters describing the moisture content of the harvested product and the proportion of total biomass that is harvested (harvest index) are used to calculate the shoot biomass and a fixed root proportion is used to calculate root biomass. Monthly N uptake is then calculated from the proportion of final biomass that is grown each month and internal parameters specifying typical N concentrations of various crops. These are calculated using crop specific parameters. Generic crop parameters such as moisture content of the harvested fraction, root depth, nitrogen content of plant parts and root proportion were obtained from the literature for most crops and complemented with expert opinion when no literature could be found. The two main sources of information in the literature were the reports of Thomas et al. (2008) and Rahn et al. (2007). The relationship describing the temporal pattern of biomass

accumulation for different crops is described below.

The total amount of N left in the field as residue is the sum of the N in the roots and stover left in the field. The amount of stover N is the product of shoot biomass yield not harvested, the N content of the stover, and a removal factor, which is function of the residue management (grazing, baling, burning, etc.). Stover and roots are considered in the residue when cultivation or harvest occurs. This also includes stover and roots from pasture when it is cultivated for cropping.

The amount of N mineralized from the residues after cultivation ($N_{RESIDUE}$) follows a decay function similar as for N_{SOM} (Equation 7), but the decay constant is proportional to the N concentration of the residue (Rahn & Lillywhite 2002).

The amount of N lost via leaching is given by the product of the available N in the soil:

$$\begin{aligned} & (N_{MIN(m-1)} + N_{FERT(m)} + N_{RAIN(m)} + N_{IRRIG(m)} \\ & + N_{SOM(m)} - N_{RESIDUE(m)} - N_{VOLATIL(m)} \\ & - N_{DENIT(m)} - N_{UPTAKE(m)} \\ & - N_{SHORTAGE(m-1)}) \end{aligned}$$

and a leaching factor (Equation 8):

$$f_{LEACH(m)} = a_{LEACH(s,m)} \left(\frac{W_{DRAIN(m)}}{W_{FC}} \right)^{b_{LEACH}} \quad (8)$$

where a_{LEACH} and b_{LEACH} are internal parameters, with a_{LEACH} specific for each soil

group, and W_{FC} is the soil water storage at field capacity.

The term $N_{SHORTAGE}$ was included to ensure closure of the N balance and enable an opportunity for feedback on the feasibility of the system being evaluated. When the crop demand (from user-specified yield) is higher than the supply (from user-specified fertilizer inputs, paddock history and residue management) the model computes a shortage of N ($N_{SHORTAGE}$, the difference between N demand and supply). When the shortage is small, the actual outcome would be a reduction in the N content of the crop. A reduction in yield would occur with larger shortages. However, the model has not been designed to account for variation in N content of the crop and as yield is user specified it cannot be adjusted by the model. Instead $N_{SHORTAGE}$ is flagged, giving the opportunity for users to review their inputs. Small values of $N_{SHORTAGE}$ may be attributed to variations in crop N concentration or uncertainties in N mineralization and therefore can be disregarded. However, when the $N_{SHORTAGE}$ value is large, the crop yield given by the user is not possible with the specified N inputs. In this case, the model stops the calculations and prompts the user to review the yield and/or fertilizer inputs.

Estimation of the model parameters

Material and methods

To estimate the parameters for OVCrop, a series of simulations using the LUCI model were performed. For these simulations, climate data measured (NIWA weather stations) between 1974 and 2002 from four distinct sites in New Zealand—Lincoln (43° 39 'S, 172° 29 'E), Gisborne (38° 39 'S, 178° 00 'E), Levin (40°38 'S, 175°16 'E) and Hamilton (37°47 'S, 175° 17 'E)—were used. These sites cover a wide range of temperature and rainfall distribution in important cropping regions. For each location, the soil was defined by one of the three generic texture classes (light, medium and heavy) and four depths to the gravel layer, which gave a variety of soil water storage capacities (Table 1).

Simulations were run for each site with treatments of different land uses including continuous fallow or different crop types planted at different times. Fallow, spring wheat, maize and potatoes were the crop types used for the leaching analysis. The simulations were run over the entire period of available climate data and were re-initialized every year. The treatments within each land use were a factorial combination of fertilizer application amounts (60, 150 or 450 kg N ha⁻¹ yr⁻¹, split into three applications) and irrigation (0, 300 and 600 mm/year, applied from October to April).

For the data analysis, the daily results from the LUCI model were first aggregated on a monthly basis. Analysis of variance (ANOVA) was then employed to verify the significance of the various factors and regression analysis was used to estimate the model parameters.

Results

Crop coefficients

The temporal pattern of crop cover and relative biomass accumulation were quantified in relation to thermal time for all crop species and planting times using a sigmoid function. A linear function was used for crop cover in the senescence phase. For a number of crops that do not have working models, the parameters were assumed from crops with similar growth patterns and adjusted for major differences such as duration and maximum cover. Examples of these relationships for spring and autumn sown wheat are displayed in Fig. 3 and information

Table 1 Soil water storage (mm) of the generic soils used in the simulations to derive the parameter values of OVCrop

Depth of soil up to the gravel layer (m)	Soil texture		
	Light	Medium	Heavy
0.20	64	84	80
0.50	70	120	110
1.00	80	180	160
1.50	90	240	210

for other crops can be found in (Wheeler et al. 2009). Location had no apparent effect on the form of these relationships, showing that thermal time is a suitable variable to account for differences in the timing of crop development observed at different places. While the same function was used for all crops and planting times, the specific parameters varied substantially depending on the crop type, especially due to duration and growth pattern (how quickly it closes its canopy and when senescence and maturity occur). A simple method to modify the crop growth parameters was also developed to take account of defoliation, for example in winter-sown wheat, seed crops and forage crops. Defoliation could be by cut-and-carry

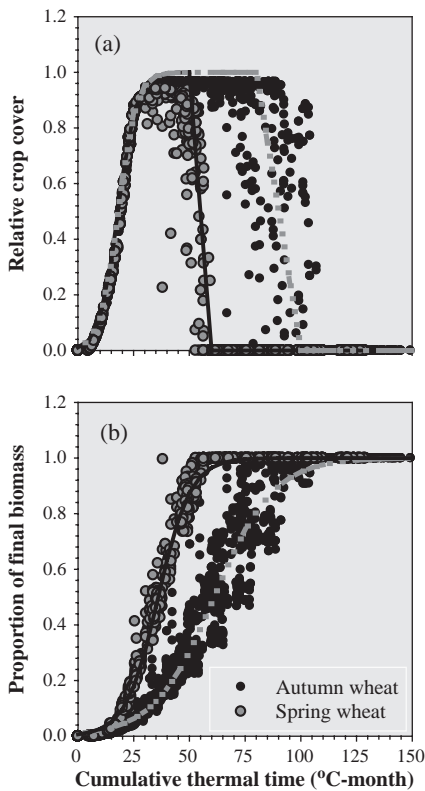


Fig. 3 Relative crop cover (a) and relative biomass accumulation (b) factors in relation to cumulative thermal time for spring and autumn wheat. Lines represent the model used in OVCrop.

or by animal grazing. The model estimates N leaching loss from animal excreta separately.

Evaporation

To determine the values of k_{EVAP0} , only simulations with a fallow land use were considered. This was done to avoid the disturbance of the effects of variable crop cover. Because k_{EVAP0} only takes effect when the water inputs are greater than the evaporative demand (Equation 2) the data were also filtered to remove months that did not satisfy this condition. The relationship between the E_{TP} and the evaporation calculated by the LUCI model for these months was then analysed. This relationship, although quite scattered, clearly deviated from the 1:1 line over the year (Fig. 4). The analysis of variance showed that this deviation varied mostly between months and was not significantly influenced by any combination of location, irrigation or soil type (Table 2). The slope of this relationship represents k_{EVAP0} , which is varied by month in OVCrop, ranging from 1.0 in winter (June to August), to around 0.5 in January and February.

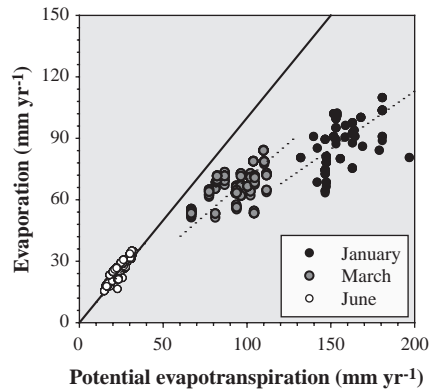


Fig. 4 Relationship between the potential evapotranspiration and the soil evaporation simulated by LUCI over 25 years under bare soil conditions, for three different months. The dotted lines have the intercept as the origin and slope representing k_{EVAP0} . The continuous line represents the 1:1 relation.

Leaching

The relationship between drainage and leaching simulated by the LUCI model exhibited considerable scatter which increased with the magnitude of drainage (Fig. 5a). The variability between different scenarios was reduced considerably when drainage was scaled by soil water storage at field capacity and leaching was scaled by leachable N (the sum of mineral N in the soil at the start of the month plus the N inputs minus the N outputs). The ratio between N leaching and leachable N is equal to f_{LEACH} (Equation 8). The scatter of this relationship, however, still increased as drainage values increased, so a logarithmic transformation was used before fitting parameters to quantify f_{LEACH} (Fig. 5b).

The analysis of variance showed that the ratio between N leaching and leachable N was strongly related to the amount of water drained (Table 3). The correlation with soil type was also considerable even though the ratio between the drainage and the soil water storage at field capacity was used to reduce the effect of soil. Other factors, such as site, month of year, crop type and the timing or amount of fertilizer or irrigation did not exhibit significant effect on f_{LEACH} . Therefore, the use of Equation 8 with its parameters (a_{LEACH} and b_{LEACH}) varying for soil properties (texture and depth to the gravel layer) was considered a suitable function for predicting f_{LEACH} . Regression analysis (REML) was then used to determine the values of a_{LEACH} and b_{LEACH} .

The estimated values of a_{LEACH} were in the range between 0.07 and 0.21, and there was no

clear tendency in their variation, apart from the heavy soil which showed smaller values for most of the depths analysed. A value of 0.941 was found for the b_{LEACH} parameter for all soil types.

Model evaluation

Material and methods

Comparison against LUCI simulations

Due to a shortage of annual measurements of N leaching at 1.5 m depth below cropping systems, a preliminary evaluation of OVCrop was conducted by comparing its N leaching estimates with those of the parent model. A set of simulations (independent of the simulations used to develop OVCrop) were conducted over a range of scenarios. Simulations were run using the LUCI model for each year from 1975 and 2000 at three sites in New Zealand—Pukekohe, 37°13'S, 174° 52'E; Hastings, 39° 40'S, 176° 51'E; and Gore, 46° 08'S, 168° 56'E). Climate data for these sites were obtained from the NIWA interpolated VCS dataset (Tait & Turner 2005; Cichota et al. 2008). For LUCI, daily data were employed, while monthly summaries were produced for the new model. All comparisons used two generic soils, defined by the light and heavy textural classes and 1.5 m depth to gravels (Table 1), four land uses (fallow, spring wheat, autumn wheat and potato), three irrigation levels (0, 300 and 600 mm, split evenly in six applications over the spring/summer period) and three fertilizer treatments (60, 150 and 450 kg N ha⁻¹, split in three applications – at sowing and another two

Table 2 Analysis of variance for the main factors influencing evaporation in months when evaporation demand was higher than water inputs. The response variable was W_{EVAPO}/E_{TP} ^a

	df ^b	SS ^c	MS ^d	F test	%Var ^e
Site	3	254521	84840	2295.1	8.1
Soil texture	2	36694	18347	496.3	1.2
Soil depth	3	5397	1799	48.7	0.2
Irrigation	2	134076	67038	1813.5	4.3
Month	11	2431813	221074	5980.4	77.3
Residuals	6856	283328	41		9.1

^a W_{EVAPO} is the monthly evaporation rate and E_{TP} is the potential evapotranspiration; ^bDegrees of freedom; ^cSum of squares; ^dMean squares; ^ePercent of variation explained

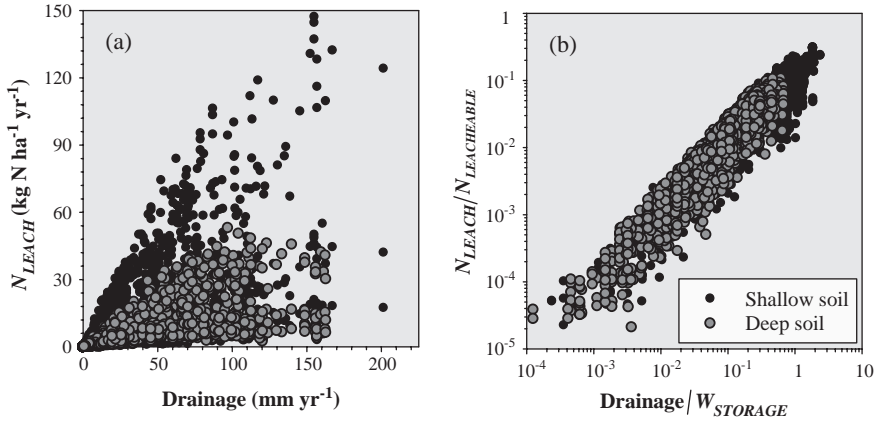


Fig. 5 (a) Relationship between drainage and N leaching estimated by the LUCI model for the Lincoln site and two soil types over a series of scenarios (see text for details). (b) the relationship, on a logarithmic scale, between the drainage scaled to the soil water storage at field capacity and the ratio between N_{LEACH} (leaching) and $N_{LEACHABLE}$ (the sum of soil mineral nitrogen at the start of the month and nitrogen inputs and removals during the month).

throughout the cropping season). All simulations were run over the 25-year period, but were re-initialized every year, thus the combination of years and sites resulted effectively in 75 different weather treatments.

For evaluating the general agreement between the models, the annual totals from both models were compared using scatter plots (with the 1:1 line) and some agreement measures, including the general bias ($GB, \%$), the mean

absolute error (MAE) and the coefficient of determination (R^2).

Comparison against measured data

The data for this comparison were obtained from an experiment conducted at Plant and Food Research in Lincoln, NZ (43°39'S, 172°29'E). The experiment aimed to determine leaching losses from different crop rotations.

Table 3 Analysis of variance for the main factors influencing N leaching. The response variable was set as $\log(N_{LEACH}/N_{LEACHABLE})^a$

	Df ^b	SS ^c	MS ^d	F test	%Var ^e
$\log(W_{DRAIN}/\theta_{FC})$	1	89914	89914	828046.9	86.85
Soil texture	3	9878	3293	30321.9	9.54
Soil depth	3	124	41	381.3	0.12
Site	3	17	6	51.6	0.02
Crop	3	193	64	593.1	0.19
Month	11	305	28	255.3	0.29
Residuals	28551	3100	0.109		2.99

^a N_{LEACH} is nitrogen leaching and $N_{LEACHABLE}$ is the sum of soil mineral nitrogen at the start of the month and nitrogen inputs and removals during the month; ^bDegrees of freedom; ^cSum of squares; ^dMean squares; ^ePercent of variation explained

Table 5 Measures of agreement between annual values of evapotranspiration, drainage, change in soil mineral N, and N leaching from simulations of bare soil and crop rotations using OVCrop and the LUCI model

	Evapotransp. (mm yr ⁻¹)	Drainage (mm yr ⁻¹)	Mineral N (kg ha ⁻¹ yr ⁻¹)	N uptake (kg ha ⁻¹ yr ⁻¹)	N leaching (kg ha ⁻¹ yr ⁻¹)
Bare soil					
General bias (%)	2.2	-3.2	1.6	-	-1.8
Mean abs. error	68.8	77.9	14.0	-	14.0
R ²	0.612	0.854	0.952	-	0.899
Crop rotations					
General bias (%)	0.4	-5.7	158.5	12.9	-11.9
Mean abs. error	56.9	65.7	23.9	50.2	10.5
R ²	0.659	0.877	0.782	0.655	0.830

the nitrogen balance were also very good, with GB under 2% and MAE just under 14 kg ha⁻¹ yr⁻¹ (Table 5). The high R² values confirm the good performance of OVCrop.

Testing water balance and leaching from crop rotation. The estimates of drainage and evapotranspiration under crop rotations using the OVCrop agreed reasonably well with the results from the LUCI model (Fig. 7) and the measures of agreement showed similar magnitude to those from the bare soil simulations (Table 5 and Fig. 7). There was also reasonably good agreement in predictions of soil mineral N and N leaching under crop rotation (Fig. 7), but results were more scattered when compared with the bare ground treatments (Fig. 6). The increased scatter may result from inaccuracies on the estimation of crop cover which affect the estimation of the water balance, or the simplified N uptake routine of the new module which tends to over-predict N uptake at lower N supplies.

Comparing long-term averages of drainage and leaching. The values of annual drainage and N leaching estimated by the OVCrop using long-term averaged weather data were nearly all within the variation range of the LUCI results, but tended to underestimate drainage at the driest site, Hastings (Fig. 8). This can be attributed to the use of averaged weather data in the OVCrop, which smoothes the extremes in rainfall that give a substantial contribution to drainage in dry environments like Hastings. Leaching also tended to be under-predicted by the OVCrop on the heavy soil, especially at low levels of N application (Fig. 8). This under-prediction was evident for crop treatments but not for fallow treatments, suggesting it can be attributed to an over-estimation of N uptake in these treatments by the simplified procedure of the proposed module.

Comparison with measured data

A good agreement between observed and predicted drainage and leaching values was found for 2005, considering the simplifications of the model (Fig. 9). OVCrop reproduced the range of leaching outcomes that the different irrigation

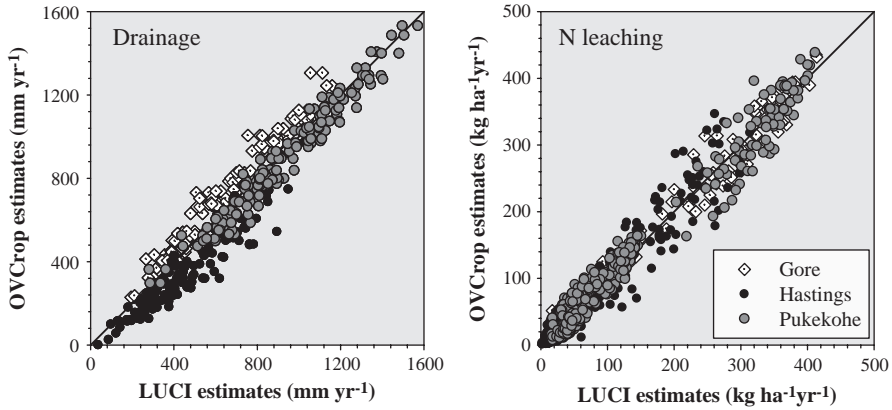


Fig. 6 Comparison of the annual estimates of drainage and N leaching under bare soil obtained using the OVCrop module and the LUCI framework for three sites in New Zealand. Points from each site represent a range of treatments and years. Diagonal line is the 1:1.

and nitrogen treatments produced and the lack of difference between the two rotation treatments. The OVCrop also predicted the relative variations in drainage and leaching between treatments in 2006 but under-predicted the absolute values of drainage (Fig. 9a) for the rotation 2 (R2) crop rotation and subsequently the N leaching (Fig. 9b). The under-prediction in drainage was caused by an over-prediction of evaporation by 120 mm yr^{-1} for R2. This disagreement was not surprising, since the water balance was designed to produce general predictions of the long-term average water balance in a

given climate, not reproduce drainage events of particular years. To provide a fair test of the N leaching routines, the drainage amount for 2006 was modified to reflect the values measured. This resulted in a very good agreement between observed and predicted leaching, thus corroborating the leaching procedure of OVCrop.

Discussion and final remarks

During the development of the module presented here, the number of parameters was kept to a minimum, and only the most

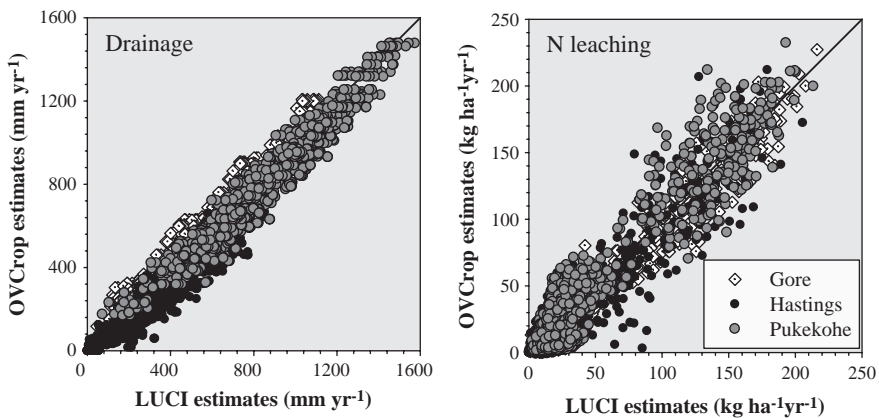


Fig. 7 Comparison between annual values of drainage and N leaching under crop rotation estimated by OVCrop and the LUCI framework for three sites in New Zealand. Points from each site represent a range of treatments and years. Diagonal line is the 1:1.

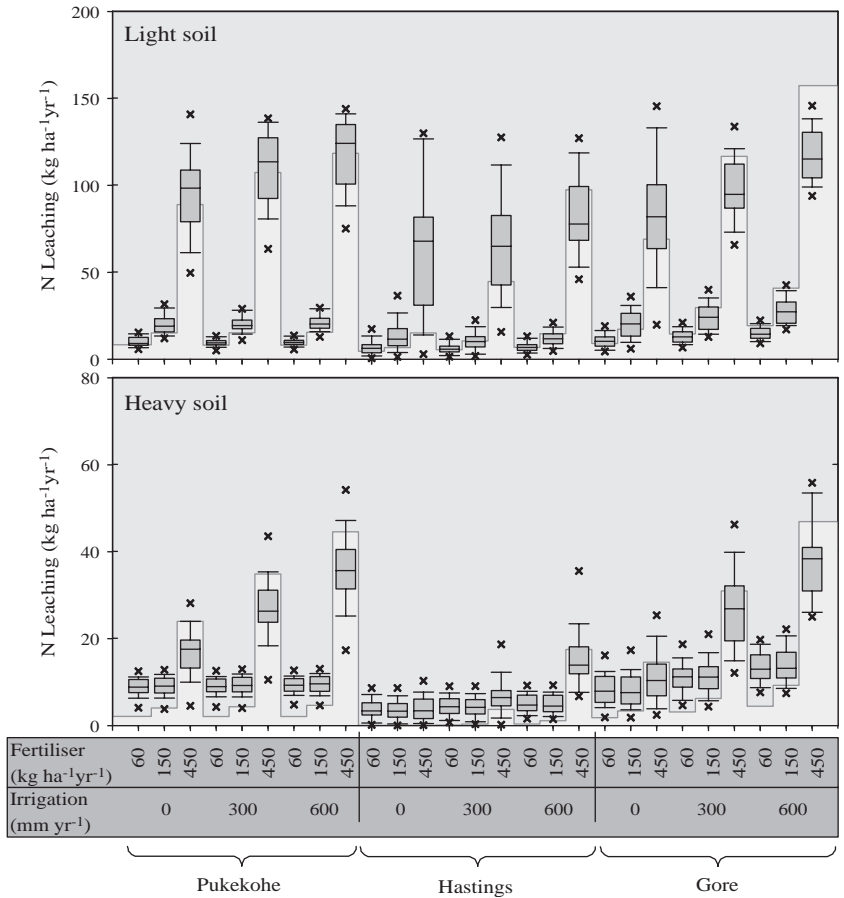


Fig. 8 Variability of N leaching predicted by the LUCI model over 25 years (boxplots) and the predictions by the OVCrop module using average weather data (bars) for three sites and two soil types. Data are from a series of spring wheat scenarios with different irrigation and fertilizer levels (see text for details).

important factors influencing N leaching estimates were taken into account. In spite of this, the water and nitrogen budgets computed using OVCrop showed very good performance. The model testing results showed that the water balance is well described by the OVCrop and comparable at an annual time scale to the predictions of the more complex, process-based, LUCI framework model. The description of the nitrogen balance is also reasonably good. The various water and N pools simulated under crop rotation present more scatter, compared with those under bare soil, but still have acceptable measures of agreement (Table 5). The main

outputs tested, drainage and N leaching, concur especially well with the predictions of LUCI over a wide range of scenarios (Figs. 6 and 7). This agreement indicates that the model is able to simulate long-term drainage and leaching over a range of situations covering most of the New Zealand conditions. It also suggests that the model may be acceptable for simulating not only long term, but also specific years, providing particular weather data instead of long-term averages. For this purpose, however, more studies and tests would be required and thus are expressly not recommended at the current stage of development.

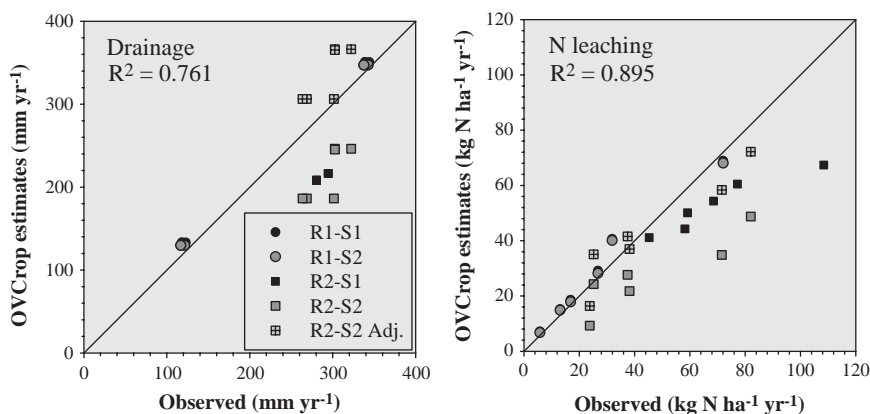


Fig. 9 Comparison between the observed and predicted values of drainage and leaching for two crop rotations (R1 and R2) and two seasons (S1 and S2). Also are shown the values for R2–S2 after adjust for water drainage (see text and Table 4 for details). Diagonal line is the 1:1.

The proposed model also compared well against the expected long-term variation. Again drainage showed very good performance, with estimates within the range predicted by the LUCI model. The performance of the proposed module for N leaching, while not quite as good as for drainage, was still very reasonable. N leaching estimated using long-term average weather data fitted reasonably well within the variation pattern predicted by LUCI, especially for bare soil or for the light soil type (Fig. 8). For the crops and especially with the heavy soil, the estimates from the proposed tool tended to be out of the variation range predicted by LUCI for the scenarios with low N values. Being at the low end, these differences are of less concern, but work for improving these predictions could be done in the future.

A sensitivity analysis has shown that the parameters of the model related to plant uptake and return via residues have a significant impact on the model output (Cichota 2009). These parameters are difficult to estimate in the field and hence have been hard-wired within the model (internal parameters) and are not available to change by end-users. Best judgement was used to produce reasonable relationships and parameters to reflect the effect of management on N mineralization, but there is a clear need for more studies on the decomposition and mineralization processes

and their contribution to soil N balance. The amount of N released in the soil from organic matter and crop residues has been found to be particularly significant, especially when converting pastures into crop land (Francis 1995; Francis et al. 1995; Stark et al. 2006). The parameters controlling evaporation and leaching were shown by the sensitivity analysis to have a considerable impact on leaching estimates through impact on drainage (Cichota 2009) and these are expected to be improved with more research.

The sensitivity study also indicated that the predictions of N leaching by OVCrop have a low sensitivity to the parameters related to the calculation of the mineralization of soil organic matter. Hence, the use of limited input data on soil mineralization is justified. An exception may be where pasture quality is suspected of affecting mineralization when converting the field into arable land (e.g. high-quality ryegrass/white clover compared with a browntop/native pasture). Research work is under way to determine whether this is due to differences in the amount of residual N or differences in mineralization parameters.

Unfortunately there were no appropriate measured datasets for comparisons of long-term predictions. The comparisons against the data obtained in the experiment with different crop rotations and management over two years showed, however, very positive results (Fig. 9).

The under-estimation of the N leaching for the second year of this experiment was due to deviations in the water balance predictions. When drainage values were adjusted, the predictions of leaching agreed very well with measured values. It should be reinforced that the model was designed to estimate long-term averages, therefore comparisons against short-term data (measured or simulated) should be done with caution. The model was not developed to be used as a day-to-day management tool as there are specific models available that are designed to do this. The model structure was designed so that as well as responding to management practices for the current crop, the model also responds to previous crop management including pasture. This construct also allows cropping systems to be compared with other land-use systems within New Zealand, and allows the crop model to be integrated into the pastoral model so that land-use changes, mixing pasture and arable farming systems can be more easily modelled. Developments under way include the full integration of pasture and crop modules, and improvements to animal fodder cropping routines.

Modelling tools have been increasingly recognized as important instruments for supporting agricultural and environmental management. The model presented here is a suitable tool to help manage soil N and to provide environmental accountability for cropping systems in New Zealand. It presents an easy-to-use interface, requiring few and meaningful inputs, with the minimum flexibility needed to set up crop rotations and management of real farming systems. The model has been incorporated as an upgrade of the Overseer model and is available for use by farmers, consultants and regional councils. It is distributed free of charge (www.agresearch.co.nz/overseerweb) to enhance its use. It is expected that further upgrades will be made as more research and data are produced.

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Note

1. OVERSEER is a registered trademark of AgResearch Ltd.

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