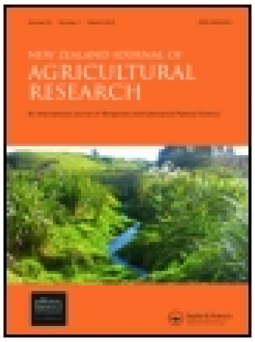

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Estimating nutrient loss to waterways—an overview of models of relevance to New Zealand pastoral farms

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Abstract Reliable estimation of nutrient losses from farmland is of increasing interest, driven by both economic and environmental concerns. Routine direct measurement of nutrient losses is currently impractical given the scale and variability of the problem. Simulation models are the best alternative and their use for assessing potential nutrient losses has been increasing worldwide. In New Zealand, there are a considerable number of models in use, or that are being developed, aiming to estimate N and P losses from pastoral fields. This range of alternative models reflects both the different level of detail and scale at which N and P losses can be estimated, and the diverse range of purposes assumed during the model development. Thus, it is important to understand the differences between models in order to select the one that will produce estimates appropriate to the intended use. This work presents an overview of the principal models for estimating nutrient loss being used or developed in New Zealand. It emphasises models that deal with N and P losses from pastoral farming systems, particularly via leaching, and that may allow the handling of different farm management procedures. Most of the models have gone through some testing and are supported by published works, although some are not fully operational yet and others need further evaluation. There is, in general, a lack of organised information about how several of these models work and what their main purposes are. We aim to supply some basic information about the available tools, sorting them into categories to highlight their primary differences and similarities. This is intended to assist discussions about model selection as well to highlight where information gaps about particular models need to be addressed.

Keywords Environmental policy; model uncertainty; model selection; OVERSEER®; NPLAS; SPASMO; EcoMod; APSIM; LUCI

INTRODUCTION

Agriculture contributes to about 50% of New Zealand's export earnings (Statistics New Zealand 2007), and the industry as a whole, particularly dairying, has recently been growing faster than many other economic sectors (Ministry of Agriculture and Forestry 2007; Treasury 2007). The productivity of dairy farms in New Zealand (kg milk solids ha^{-1}), for instance, increased by more than 15% during the 1990's, resulting from gains in both the production per cow and the number of cows per hectare (Livestock Improvement 2006). This gain in productivity has been accompanied by increasing farm inputs. In the same period, for example, the use of phosphorus (P) fertiliser in New Zealand has doubled and the use of nitrogen (N) fertiliser increased five-fold (Ministry for the Environment 2006; Statistics New Zealand 2006). This increase in fertiliser inputs, and consequently in stocking rates, may lead to elevated nutrient losses from farms.

The impact of agricultural intensification on the environment is increasingly a matter of public concern, and several regulations have recently been passed, or are being considered, in order to limit damaging effects on the environment (Parliamentary Commissioner for the Environment 2004; Dragten & Thorrold 2005; Horizons Regional Council 2007). Aware of this, the industry has launched programs such as the Sustainable Environmental Management Strategy (Dairy Insight 2006) to better understand

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and reduce these impacts. Fonterra, the main dairy company in New Zealand, and several regional councils are promoting or requiring the use of nutrient budgets to support farm nutrient management, especially for more intensive uses such as dairy farming (Ledgard et al. 2004; Monaghan et al. 2007). Two approaches can be taken for calculating nutrient budgets: measurement and modelling.

The impacts of agriculture in a catchment can be measured, for example, by monitoring the quality of the water bodies in the area, but the identification of the impact level of particular farms or the different land uses and management practices is much more difficult. Routine direct measurement of nutrient loss at a farm or paddock scale is currently not feasible. While some measurement methods are available, their spatial or temporal scales often do not correspond with that required for monitoring. The methods can also be time consuming, costly, and generally the measures display large variability (Addiscott 1995; Oenema et al. 2003). The alternative to measurements is the use of computer simulation models. Based on the knowledge of the processes involved and with support of available data, researchers can build models that can simulate the farming systems. With these models, the possible impact of different land uses and management practices can then be predicted.

In light of the increasing practical importance of nutrient simulation models, the objective of this paper is to present an overview of the models that might be useful for the routine estimation of N and P losses to waterways from pastoral farms in New Zealand. As water quality is of increasing concern nowadays, we concentrate this review on the loss pathways that affect water quality (leaching and runoff) rather than on all loss pathways. We will also focus on models that deal with pastoral farming systems and emphasise the impacts of farm design and management procedures on N and P losses, and that have the potential to be used routinely across a large number of farms. We also review a few more specialised models that might have a supporting role in the analysis of specific issues or could be used in the future development of the models suitable for routine usage. Our overview focuses on the major models currently available and in use in New Zealand, and presents a selection of models able to handle problems on a wide range of scale, detail, and uncertainty. With this overview we expect that the parties interested in using modelling tools or their results, whether for management, research, or policy making, will have a guide for reference.

BACKGROUND

Modelling is an important method for comprehensively integrating the knowledge of basic processes and describing a system beyond that which can be accomplished using subjective human judgments (Bywater & Cacho 1994; Hutson 2003). Estimation of production, irrigation, nutrient balance, and leaching of chemicals are some of the subject areas where models have most frequently been applied in agricultural management.

Several different modelling approaches have been used to evaluate nutrient losses from farm systems, covering a broad range of scale and purposes, with varying levels of detail and uncertainty (e.g., Di & Cameron 2000; Close et al. 2003; van Beek et al. 2003; Elliott et al. 2005; Shorten & Pleasants 2007; Vogeler et al. 2007; Johnson et al. 2008). While all these models produce an estimate of the nutrient balance of the system or area, their complexity can vary greatly, according to the development approach and assumptions, and the intended usage (Addiscott 1995; Boote et al. 1996; Rykiel 1996; Cichota & Snow 2008). The varying level of detail in these models is mostly regarding the number of pools and processes considered in the balance (Fig. 1 and 2). The main difference between the models is how each item in the nutrient balance is estimated. The estimates can be produced in some models using complex mechanistic, or process-oriented, descriptions of a reasonably large number of processes involved in the nutrient dynamics (Fig. 2). Conversely, there are models that use simpler, typically empirical, descriptions of those processes, and may take fewer items into account (Fig. 1).

Simple models are typically associated with large spatio-temporal scales, for example annual averages of nutrient losses on a paddock, farm, or catchment (Fig. 1). The description of the system in such models can be simplified because the variability of many processes tends to decrease at large scales (Beven 1989; Addiscott 1996; Lin et al. 2005). To track the variation of processes at small scales, however, greater detail must be included in the model (Fig. 2) and so the model becomes more complex. The more complex the model, the more information about the system is usually required for obtaining its parameters. However, these models can usually be set up with greater specificity, and although specificity does not directly imply accuracy, it certainly effects the perception of the user and their subsequent confidence in the model (Brown & Bewsell 2008). It should be noted that although there is no hard boundary separating simple and complex models,

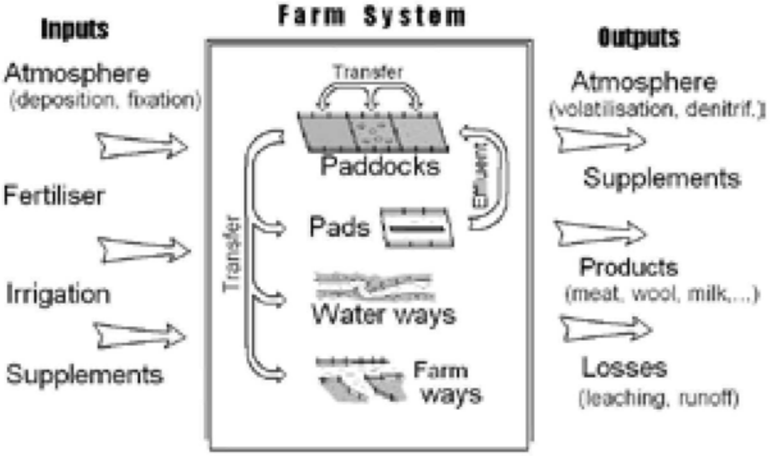

Fig. 1 Simplified schematic of a nutrient balance over a large scale area (farm system).

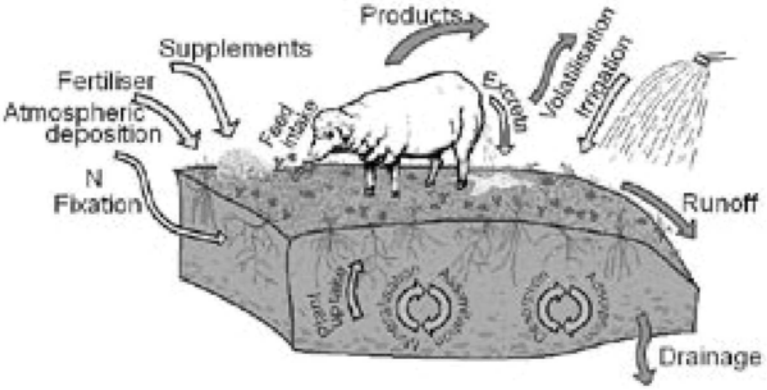

Fig. 2 Schematic of the cycle and processes involved in the nutrient balance in a pastoral field.

this terminology can be helpful for the discussions in this work.

Complex models, describing natural and managed systems with great detail, are common tools for scientific research and consulting (Addiscott & Tuck 2001; Beven 2002; Keating et al. 2003). Although there is large variation between these models, their basic characteristics include the capacity to work at various temporal and spatial scales (small scales in particular), to handle a large variety of processes, and may include simulations of complex farm management. Simple nutrient budget models have become common tools for the analysis and management of farming systems on a basic level. These models have also been used for general evaluation of the sustainability of production and environmental standards of farms, catchments, and even countries (Goodlass et al. 2003; Kutra & Aksomaitiene 2003; Schlecht & Hiernaux 2005; Gourley et al. 2007). Although a nutrient budget does not provide detailed information, it is an easy, simple, and flexible tool for estimating the amount of nutrient available or that is required to sustain a productivity level (O'Connor et al. 1996; Scoones & Toulmin 1998; Oenema et al. 2003).

The use of simulation models in New Zealand has been accelerating in recent years, as their importance for research and environmental analysis is recognised. Measuring nutrient loss at an appropriate scale for assessment is time consuming, costly, and subject to large variability. Modelling can play a key role to overcome these challenges.

There is an apparent overlap of what seems a large number of models available or being developed for this purpose (Dairy Environment Review Group 2006; Brown & Bewsell 2008). This is a result of the different levels of detail and scales at which N and P losses can be reported. Also, some scepticism seems to arise from the lack of information about the basis and validation of these models (Brown & Bewsell

2007, 2008). Because different models are appropriate for different purposes, it is important to know what they can and cannot do compared to the users' needs, so that the most appropriate model is selected.

MODELS FOR FARM NUTRIENT LOSS ESTIMATION USED IN NEW ZEALAND

The most relevant models being used or developed in New Zealand to compute nutrient balances in agricultural fields are listed in Table 1. These models can be used to obtain estimates of losses at various scales, taking into account different land uses and management practices. Given the range of alternatives, it is important to know both the strengths and the limitations of these models in order to choose the best tool for a given task. Initially, two groups of models for estimating nutrient losses at paddock/farm level are identified. These are simpler average type models and the more complex dynamic systems models, which are discussed below. Some models for larger scales or higher level of detail are also shown in Table 1, but will be discussed later.

Long-term average type models (nutrient budgets)

These models focus on calculating the balance of nutrients on a long-term annual average basis. The scale of their predictions is paddock or farm, and most of the processes have relatively simple and empirical descriptions. Two models in this category are discussed, both developed and in use in New Zealand, and which demand only a moderate level of expertise to use.

OVERSEER®

The OVERSEER® model (Ledgard et al. 1999; Wheeler et al. 2003, 2006) uses empirical relationships, internal databases, and readily available data from an "existing" farm to estimate the nutrient inputs and outputs at farm or paddock scale, and presents them as a nutrient budget. Here an "existing" farm refers to the fact that OVERSEER® does not simulate production but instead requires farm productivity and farm inputs (fertiliser, supplements) as inputs to the model. These quantities are usually known for existing farms or can be estimated for hypothetical farms using models such as Farmax (Marshall et al. 1991; Webby et al. 1995) or Udder (Larcombe 1999). Using the nutrient budget and indices derived from it, such as farm nutrient efficiency, the model can be used to examine the impact of nutrient use and flows within a farm. Both nutrient use efficiency and environmental impact are assessed, and the effect of implementing some mitigation options can be investigated (Wheeler et al. 2003, 2006; Ledgard et al. 2004).

Table 1 Summary of several models available for estimating nutrient loss from pastoral farms. M, mechanistic; P, process-oriented; E, empirical; Q, quasi-empirical; P/p, Point/paddock; P/f, Paddock/farm; F/c, Farm/catchment; C, Catchment.

Model	Main subject	Type	Scale	Primary reference
Daily or sub-daily time-step				
APSIM	Biophysical	P	P/f	Keating et al. (2003)
Crop calculators	Plant physiology	P	P/p	Li et al. (2007a)
DNDC	Biochemistry	P	P/p	Saggar et al. (2007b)
EcoMod	Biophysical	P	P/f	Johnson et al. (2008)
GLEAMS	Biogeochemistry	P	P/p	Leonard et al. (1987)
HYDRUS	Biogeochemistry	M	P/p	Simunek et al. (2005)
LEACHM	Biogeochemistry	P	P/p	Hutson (2003)
LUCI	Biophysical	P	P/f	Jamieson et al. (2006b)
RoTaN	N loss	E	C	Rutherford et al. (2006)
SPASMO	Biogeochemistry	P	P/p	Green et al. (2004b)
Annual average estimates				
AquiferSim	N in groundwater	Q	C	Bidwell & Good (2007)
CLUES	N and P loss	Q	F/c	Woods et al. (2006)
EnSus	N leaching	E	F/c	Stephens et al. (2003)
NLE	N leaching	E	F/c	Di et al. (2005)
NPLAS	N and P loss	E	P/f	EBoP (2007)
OVERSEER®	N budget	E	P/f	Wheeler et al. (2006b)
SPARROW	N and P loss	Q	C	Schwarz et al. (2006)

The model has been developed reviewing the knowledge obtained primarily in New Zealand and in consultation with end-users (farmers, consultants); thus it is well suited for handling management practices and environmental conditions particular to New Zealand. OVERSEER® has been specifically designed to require minimum input with data that are meaningful to farmers and easily obtained (AgResearch 2007). For reliable performance, the OVERSEER® model requires that reasonable input data are given (Wheeler 2009). This implies, for example, that the amount of fertiliser required to support the given level of production needs to be known. It is also assumed that the system is in quasi-equilibrium and that good management practices are followed (Ledgard et al. 1999). The model is designed to predict the long-term average behaviour of the system and so it is not suitable for examination of extreme-case scenarios or systems in transition. Likewise, it is not suitable for estimating nutrient losses from particular years.

OVERSEER® has three major sub-programs or modules: pastoral, cropping, and horticultural. Currently the model's strength lies in the pastoral module, where more research and data for calibration are available in New Zealand. Work to strengthen the cropping and horticultural modules is currently underway (Whiteman & Brown 2009). From the early versions, where the nutrient budget comprised N and P, the model has evolved to include several other nutrients and pH. Also, an estimate for greenhouse gas emission (CO_2, N_2O, and CH_4) using inventory methods is now given (Wheeler et al. 2003, 2006).

Initially OVERSEER® was primarily used to assist fertiliser management, but it has evolved to become a tool for evaluating farm systems, including its impact on the environment (Wheeler et al. 2006). OVERSEER® is widely used in New Zealand as a decision support model by consultants. Training in the usage of the model has been integrated into a study programme on sustainable nutrient management at Massey University (FLRC 2008). OVERSEER® has also been used in a series of studies for evaluating different systems and scenarios, for comparing nutrient efficiency of New Zealand farms with overseas counterparts (Ledgard et al. 2000; Thomas et al. 2005), and to examine the effects of land use change and management practices on nutrient loss (Condron et al. 2000; Ledgard et al. 2001; Ledgard & Power 2006). More recently the model has also been used to monitor farm nutrient losses as an instrument for applying new environmental policies (Dragten & Thorrold 2005; Horizons Regional Council 2007).

NPLAS (Nitrogen and Phosphorus Load Assessment System)

NPLAS has been developed by the National Institute of Water and Atmospheric Research (NIWA) in conjunction with Environment Bay of Plenty (EBoP) and AgResearch. NPLAS is intended as a tool to estimate N and P loss, either to streams or to the ground water, from properties in the Rotorua Lakes catchment. NPLAS uses empirical relationships derived from the OVERSEER® and GLEAMS (Knisel & Davis 2000) models calibrated to the Rotorua catchment to describe the effect of farming systems on nutrient loss (EBoP 2007). It calculates long-term averages of nutrient loss based primarily on land use, with minimal or generic information on farm management. NPLAS (EBoP 2007) accounts for various land uses, including pastoral farming, cropping and horticulture, and also forestry, native bush, recreational, and urban uses. The model allows investigation of the impact of protection features, such as fencing waterways and the presence of wetlands, on nutrient loss. These features are set at different qualitative levels of effectiveness, which were set based on literature values and general knowledge (EBoP 2007). A free version of NPLAS was released in 2006, and can be operated via the internet running from the EBoP web server. This model was released for tests and further development was planned (D. Ede, 2007 pers. comm.). However, upgrades made on OVERSEER®, including most of the differential features of NPLAS, such as the consideration of wetlands, make it likely that NPLAS will be phased out in favour of OVERSEER® (S. Elliot, 2008 pers. comm.).

Dynamic paddock and farm system models

In this category four model frameworks are reviewed. These models work with complex systems on daily or sub-daily time steps and are capable of simulating quite different systems by using different sub-models or modules that handle the specific processes. All of these models are suitable for simulating some aspects of New Zealand farm systems, however the focus and strength of each model are quite different, particularly when considering their potential to model whole farm systems. The areas of overlap between these models are only partial.

SPASMO (Soil-Plant-Atmosphere System Model)

SPASMO (Green et al. 2003a, 2004b) is a detailed process-orientated model developed by HortResearch (now Plant and Food Research) for simulating the interactions in the plant-soil-water system. It has been developed using well established international scientific knowledge, but has been adapted and tested using research developed in New Zealand conditions. Early versions of the model have been used since the late 1990s, and it has been continually improved with the implementation of more detailed routines and the addition of procedures to handle the various processes in the soil.

Water flow through the soil is simulated in SPASMO using a water capacity approach (Hutson & Wagenet 1993), and allows the specification of a mobile and an immobile fraction (Addiscott & Whitmore 1991). The model has a simple routine to simulate plant growth, similar to that of Eckersten & Jansson (1991), and plant water uptake that can be adapted to one of several different crops ranging from pasture to vegetables to kiwifruit vines. The transport of nutrients is estimated after computing the outputs of processes such as fertilisation, plant uptake, volatilisation, exchange and transformation in the soil. Most of the processes in the soil are simulated assuming first-order relationships, and can have weighting factors to account for abiotic influences, such as temperature and soil moisture (Green et al. 2003a).

SPASMO has been used mainly for horticulture, where usually only single paddocks are considered. It is possible to set up the model to simulate variability within the farm (Green et al. 2007), however, the model itself does not deliver outputs for the whole farm. This integration has to be made indirectly, post-simulation, by the user by combining the outputs from several model runs (S. R. Green, 2007 pers. comm.). A set of rules defined *a priori* are used to control fertilisation, irrigation, and other management practices for the simulated paddock. For pastoral simulations, the model uses rules for grazing/stocking following a pre-defined schedule, with supplement being brought in if feed is insufficient. Nutrients excreted by animals are the result of a balance between the intake and the requirements for maintenance, growth, and production. The remaining nutrients are returned to the soil as urine and dung and are assumed to be uniformly distributed over the paddock.

Being a process-oriented model, SPASMO can be made quite specific to a particular area provided the necessary soil and weather conditions are known. This can provide some advantage over the simpler nutrient budget models, but the cost of this specificity is that the model needs more input data. However, in this respect, SPASMO is still simpler than some of the soil process models presented below (Sarmah et al. 2006).

SPASMO is a flexible model framework; the addition of different modules enables it to be adapted for specific systems, but it does not have a well developed end-user interface. It is, thus, an expert-user model and is not directly available beyond HortResearch. The SPASMO model has been widely used in research, such as in the evaluation of N leaching from pastoral and horticultural land (Green et al. 2000, 2003a; Rosen et al. 2005), estimation of water use by plants (Green et al. 2003b, 2004a; Vogeler et al. 2004), and assessment of pesticide transport in soils (Close et al. 2003, 2006; Sarmah et al. 2005). The GROWSAFE™ calculator (Snow et al. 2004), a tool developed to evaluate risk of pesticide leaching and residual build-up in agricultural soils, has been created using estimates of pesticide dynamics simulated by SPASMO using an extensive combination of crops, regional climates and soil types across New Zealand.

EcoMod

EcoMod is a biophysical model designed to simulate pastoral systems of New Zealand and Australia (Johnson et al. 2008). The farm is subdivided into a user-defined number of paddocks where attributes such as soil properties, pasture species, irrigation and fertiliser management can be defined. The model integrates these paddocks into a farm by controlling the grazing of a mob of animals around the paddocks, with supplements made or fed out depending on pasture supply and the animal feed demand. EcoMod is able to simulate dairy, beef, sheep, and deer systems. Water and nutrient processes are simulated in detail within each paddock. Water balance, including runoff and leaching, and nutrient (N, P, K, and S) and organic matter dynamics are simulated by specific modules. Farm performance and nutrient losses are estimated, including greenhouse gas emissions (Johnson et al. 2004). EcoMod, and its partner DairyMod, have evolved from the SGS (Sustainable Grazing Systems) model (Johnson et al. 2003) and so has its strengths in pastoral systems.

EcoMod accounts for several processes with a relatively high level of detail, thus a large amount of input data is required to set up a farm simulation, similarly to SPASMO. The user interface of Ecomod, however, is comprehensively developed. Nonetheless, EcoMod should be considered a research model rather than a decision support tool. EcoMod can be set up to investigate the implications for urine nutrient return into patches rather than the uniform distribution that is commonly assumed in most process-oriented models (Snow et al. 2009a,b). To date, model usage has included testing against measured dryland and irrigated pasture growth rates in the South Island (White et al. 2008) and testing of pasture growth against several Australian and New Zealand datasets (Cullen et al. 2008). EcoMod was also used to explore the potential for several leaching mitigation options for the Lake Taupo catchment (Bryant et al. 2007, 2008). The model is being adapted to fit into the APSIM modelling framework, described below (R. J. Eckard, 2008 pers. comm.).

LUCI, the Crop Calculators, and FarmSim

LUCI (Land Use Change and Intensification) is a model framework for simulating, at a paddock scale, changes in drainage, and N leaching from different land uses and management systems (Jamieson et al. 2006b; Zyskowski et al. 2007). This model, still under development, can predict plant growth and nutrient leaching. It is based on the crop calculators developed by Crop and Food Research (now Plant and Food Research). The Crop Calculators (Li et al. 2007a), already being used in New Zealand and the United States, have an easy-to-use interface that allows land managers to investigate tactical irrigation and fertiliser management in their paddocks. These calculators focus on a single cropping season.

The LUCI model dynamically simulates plant growth, mineralisation and C and N processes in the soil and the key components of the water balance. LUCI is designed to track these processes over several years. The Sirius Wheat Model (Jamieson et al. 1998; Jamieson & Semenov 2000) was the starting point for the development of LUCI but the model can now simulate several other crops, such as potato, maize, peas, and forage brassica (Wilson et al. 2004, 2006; Zyskowski et al. 2004; Jamieson et al. 2006a; Li et al. 2006). A module for ryegrass/clover pasture is under development (Snow et al. 2007c) and methods for implementing variability associated with urine patches are being investigated (Snow et al. 2007b).

A collection of LUCI paddocks can simulate a farm. This integration is done by FarmSim (Lilburne et al. 2006), and includes a description of farm management. FarmSim is intended to account for the effect of integrating different land uses and supplying information to a groundwater simulation model, AquiferSim (Bidwell & Good 2007). AquiferSim then integrates the outputs of the various farms to estimate the effect of farm management on ground or surface water. With this integration the model is useful for crop and pasture management at small scales as well as for environmental monitoring and policy analyses at larger scales (Jamieson et al. 2006b; Lilburne et al. 2006). LUCI and FarmSim form part of the suite of tools being developed within the Integrated Research for Aquifer Protection research programme (IRAP 2008).

APSIM (Agricultural Production systems SIMulator)

This model framework has been developed by the Agricultural Production Systems Research Unit in Australia and is designed to simulate biophysical processes of farming systems (Keating et al. 2003; APSRU 2008). APSIM is a flexible platform for studying the impacts on agricultural production, economics, and environmental outcomes caused by changes in the climate and/or in the management system.

The framework of APSIM comprises several biophysical modules to simulate specific processes, a series of management modules to account for the variation in the farm management, an input/output module to interface with the user, and an engine that links and controls these modules (Keating et al. 2003). In the APSIM framework, the user can choose the modules to be used, and when based on the Common Modelling Protocol (Moore et al. 2007) different modules can be easily added as they are developed. These new modules can be developed independently by researchers interested in using APSIM's management scripting module or any other module. This framework gives considerable flexibility to set up simulations and allows the re-utilisation of modules for different jobs, avoiding overlaps and saving development time (Holzworth et al. 2009). APSIM modules developed so far are mostly based on cropping systems (APSRU 2008) but there are modules able to handle pastoral and natural vegetation systems being developed (Huth et al. 2001; Whitbread & Clem 2006). The amount of input data required to set up APSIM simulations depends on the way the individual selected modules were built, but a relatively large number of parameters is generally necessary. Consequently, until now this model has mostly been used for research and consulting. Recently a simplified interface (Yield Prophet®) has been released in Australia for use by farmers (Hunt et al. 2006). APSIM's application in New Zealand is still limited, but increasing. Publications include simulations of drainage and runoff in tile-drained soils (Snow et al. 2007a) and some studies on climate change impact on plant growth (Asseng et al. 2004). In addition, the APSIM framework is being used to add management flexibility to the EcoMod model (S. Rains, 2008 pers. comm.).

MODELS FOR NUTRIENT LOSS ESTIMATION AT DIFFERING SCALES

Catchment models

The scale of a catchment is typically larger than that of a farm, and generally several farms are enclosed within the catchment area. Environmental assessments and policies are often defined, however, at catchment scale as they are natural partitions of the environment with respect to water flow. Therefore, catchment models are of interest mainly to regional councils and national governmental authorities. There is considerable variation in the scope of catchment models. Typically these models deal with a simplified level of detail regarding the different land uses, however, they should include all the significant land use types present in the area and should deal with point sources of nutrient loss (Alexander et al. 2002b; Schlecht & Hiernaux 2005). These models also may handle groundwater flow and attenuation of nutrients in the groundwater and streams. Because the effect of the different land uses may depend on their relative position in the catchment (e.g., Refsgaard et al. 1999; Alexander et al. 2002a; Bidwell et al. 2005; Schlecht & Hiernaux 2005), these models are often built coupled with a mapping tool, such as geographic information system (GIS). The temporal scale of catchment models varies depending on the processes being considered and its purpose.

Some of the models presented in this category can also produce nutrient balances at smaller scales, but this has not been their primary use. All models have been developed or calibrated in New Zealand to simulate catchments at varying scales.

EnSus (Environmental Sustainability)

EnSus is a framework model for assessing and mapping the relative risk that different land uses represent to soil and water quality (Stephens et al. 2003). This model combines maps of soil vulnerability with land use pressure to produce risk and management maps. Economic and social values are also included (Hewitt & Stephens 2002). All of the information stored in a database is linked to a GIS to produce the maps (Stephens et al. 2002). The model has been prepared for use at catchment, regional or national scales, although it is possible to use it at smaller scales provided the appropriate maps are supplied. The vulnerability of a soil type for N loss is estimated by the difference between the potential leaching from the soil and the attenuation factors applied during transport to the groundwater or water body (Woods et al. 2006). Potential leaching is obtained by combining a soil permeability factor and a climate factor (rainfall to evaporation ratio, plus an index of available water), while attenuation factors represent the occurrence of denitrification in wetlands and anaerobic soils. In EnSus, it is possible to incorporate expert knowledge within the database information to make predictions of the risk for some defined hazards.

The EnSus framework is appropriate for analysis of risk where good mechanistic models are lacking, and/or the data is patchy. Its use is still limited, but applications are set to increase as it will be incorporated into the CLUES package as described below.

NLE (Nitrogen Leaching Estimation)

NLE is a semi-empirical model designed to produce estimates of the annual averages of N leaching from different land uses into the ground water. In its first version, the model used an empirical relationship between the potentially leachable N and the concentration of N in the drainage water (Di & Cameron 2000). The potentially leachable N was determined by balancing the annual fluxes of the major N cycling processes. Empirical or functional relations for each of the annual N fluxes were determined in experiments, either using lysimeters or in the laboratory. The relationship between the amount of N that is potentially leachable and the amount that actually leaches was empirically determined and tested against published data (Di & Cameron 2000). The differences between land uses and management are accounted for in the nutrient balance. A newer version of NLE estimates the amount of N leached into the ground water in a given catchment area by computing the relative effect of the different land uses (Di et al. 2005). A different, but constant in time, N concentration in the drainage water is assumed for each land use. The amount of water leached is estimated by a water balance.

This model has been developed at Lincoln University and tested against data from Canterbury. The model would need calibration for application in other regions. NLE could be used at farm or catchment levels but its use is not widespread (H. J. Di, 2007 pers. comm.).

SPARROW (SPAtial Referenced Regression On Watershed attributes)

The SPARROW model is a semi-empirical model developed in the United States for estimating nutrient yield in catchments and the load at its discharge point (Alexander et al. 2002b; Schwarz et al. 2006). The model uses a mechanistic structure to correlate nutrient flux in streams and spatial data on nutrient sources, landscape characteristics, and stream properties. Landscape is characterised by soil permeability, drainage, and temperature. The nutrient sources (land uses or point sources) are defined by specific coefficients (Alexander et al. 2002a). The relationships within the model must be calibrated to the catchment in study.

SPARROW has been adapted by NIWA to estimate N and P loads from most catchments throughout New Zealand (Elliott et al. 2005). However it has not been validated for very small catchments. As this is a large scale model, SPARROW is primarily used to assess the status and performance of catchments (Alexander et al. 2002a). It is also being incorporated into the CLUES framework.

ROTAN (ROtorua and TAupo Nitrogen)

The ROTAN model was developed to estimate nitrate leaching to groundwater and then to streams and further to the lakes of the central North Island of New Zealand (Rutherford 2005; Rutherford et al. 2006). This proprietary model was proposed after increasing concern about the quality of the water bodies of this region. The model simulates the balance of the main water inputs (rainfall), the transfer processes (infiltration, percolation), and outputs (evaporation, streamflow). Streamflow is calculated from the outflow from three conceptual reservoirs (Rutherford 2005), representing quick shallow sub-surface flow (time scale 1–2 days), slow subsurface flow (2–10 days), and groundwater (weeks to years). Two different approaches are being tested to estimate nitrate loads into groundwater and streams, but the nitrate loss from the soil for different land uses need to be given and OVERSEER® and NPLAS are initially being used for this purpose (Rutherford et al. 2006). The model is being validated with the collection of new data (K. Rutherford, 2007 pers. comm.).

CLUES (Catchment Land Use and Environmental Sustainability)

CLUES is a model framework which combines OVERSEER®, SPARROW, SPASMO, EnSus, and HC model (an economic model from Harris Consulting) to predict environmental and economic implications of land use or management changes (Woods et al. 2004, 2006; Semadeni-Davies et al. 2006). The CLUES-GIS framework can be iteratively handled by users to specify land uses and to produce maps of nutrient yields, leaching, and economic costs. Currently CLUES is able to predict annual averages of N and P yields and losses at sub-catchment scale (Semadeni-Davies et al. 2006). Several land uses can be selected, and different scenarios can be compared. Not all of the components are presently integrated within the CLUES framework; the model is still in development and will require further validation (Woods et al. 2006).

AquiferSim

AquiferSim the key modelling tool for aiding environmental policy analysis that has emerged from the IRAP research programme (Lilburne et al. 2006; IRAP 2008). AquiferSim is a regional-scale groundwater model designed to evaluate the effect of N leaching on the quality of the underlying groundwater (Bidwell & Good 2007). The input information required includes climate data, land use, and aquifer properties, and is given in the form of GIS layers, at a 1 ha spatial resolution (Bidwell et al. 2005; Bidwell & Good 2007). The surface inputs are used to reference a lookup table of annual average drainage and N leached from the root zone of the appropriate land use. These values have been obtained from experimentation or an appropriate simulation model.

To evaluate, in few minutes of simulation, the effects of future land-use scenarios at a scale of several thousand square kilometres AquiferSim uses various scaling strategies. These range from the development of a dedicated steady-state model (Lilburne et al. 2008), to a series of specific simulation exercises that identified key processes and factors, and appropriate simplifications (e.g., Snow et al. 2007b). AquiferSim is still on development, and is to be installed at Environment Canterbury. Council staff will be able to run simulation in order to determine the likely effect of proposed land-use rules on nitrate leaching and drainage and then on groundwater quality.

Soil process models

The models under this category are all process-oriented, although the degree of complexity varies amongst them. These models were developed primarily for analysing soil processes. Detailed plant and animal processes are mostly beyond the scope of these models and the effect of different management on the nutrient balance is generally assessed indirectly. These models have been developed in the United States but are recognised worldwide and have been applied in New Zealand.

GLEAMS (Groundwater Loading Effects of Agricultural Management Systems)

GLEAMS was introduced in the late 1980s, having been developed as an extension of the CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) model (Leonard et al. 1987). GLEAMS simulates the loadings of water, sediment, pesticides, and nutrients at the bottom of the root-zone from a homogeneous field, based on complex climate-soil-management interactions (Knisel & Davis 2000). It was developed to evaluate the impact that differing management systems, such as cropping rotations, irrigation, and tillage operations, have on the potential for chemical leaching. GLEAMS uses a tipping-bucket approach to simulate water movement in the soil, and its solute movement also uses simpler approaches than the other models described below.

The GLEAMS model has been used in many studies on water and solute movement worldwide and it is part of the USDA-NRCS repertoire of operational models. In New Zealand, GLEAMS has been used to simulate N mineralisation and leaching in Canterbury soils (Webb et al. 2001; Lilburne & Webb 2002; Lilburne et al. 2003), and to evaluate the movement of pesticides in several soils (Close et al. 1999, 2003; Sarmah et al. 2005, 2006; Dann et al. 2006). GLEAMS has been employed in the development of NPLAS (EBoP 2007).

LEACHM (Leaching Estimation And CHemistry Model)

LEACHM comprises several modules of a process-based simulation model designed to describe the soil water regime and chemistry and the transport of solutes in unsaturated or partially saturated soils (Hutson 2003). It is primarily a research model, used for simulating water and chemical transport down into the soil profile (one dimension, up to 2 m). There are several versions of the model, each sharing common descriptions of the water balance and solute movement but with different "chemistry" modules. The LEACHN version simulates N dynamics. LEACHM simulates plant growth at a very simple level only to obtain estimates of water and solute uptake. Simulations of plant growth with varying system management has been done coupled with other models (Mohtar et al. 1997). GIS integration has also been developed by third party researchers (Macur et al. 2000). LEACHM has been used in a wide variety of studies worldwide. In New Zealand, it has been recently used for estimating nitrate leaching at an effluent treatment site (Mahmood et al. 2002) and in a series of nationwide studies on pesticide leaching (Close et al. 1999, 2003; Sarmah et al. 2005, 2006; Dann et al. 2006).

HYDRUS

HYDRUS is a software package developed to simulate the movement of water, heat, and multiple solutes in variably saturated media (Simunek et al. 2005). The flow media can be composed of non-uniform soils, with dual porosity formulation possible in later versions. Two different distributions are available, HYDRUS-1D for one-dimensional simulations, which is a stand-alone freeware package (HYDRUS 2008), and HYDRUS (formerly known as HYDRUS-2D), which allows simulations in two or three dimensions. The model uses numerical techniques to solve mechanistic water and solute transport equations. The flow can occur in the vertical, horizontal, or any given inclined direction. The soil layering can be arbitrary and the monitoring depth(s) can be specified. HYDRUS does not simulate plant growth or system management; only a sink term to account for plant water uptake is available. Two interesting features of HYDRUS are its ability to model solute transport with dual-domain porosity and capacity for simulations in 2 and 3-D. These features maybe useful for assisting the development of simpler models that do not explicitly acknowledge the presence of non-equilibrium flow processes.

The HYDRUS model is widely recognised and has been used in numerous studies, chiefly in the United States and Europe. It has been used in New Zealand to simulate the water regime in lysimeters (Mertens et al. 2005), the nitrate and bacteria movement towards groundwater (Pang et al. 2006), and in several studies on pesticide leaching (Close et al. 1999, 2003; Pang et al. 2000; Sarmah et al. 2005, 2006; Dann et al. 2006).

Other models

There are a considerable number of models available that have not been considered in this review in order to keep it within the proposed scope. Some are briefly mentioned here to highlight the range of applications for simulating nutrient losses from farmland. The main focus of this review is the description of nutrient losses via leaching, which is a major cause of economic and environmental concern. Lately, however, there has been increasing efforts to improve the description of gaseous losses from farming systems, especially N_2O. These losses are in general of low significance for computing the N balance, but they can be highly important for issues such as climate change. Some of the models already presented, such as EcoMod and APSIM, also produce estimates of gaseous losses, but there are others built especially for this purpose. The most developed model for simulating gaseous losses in New Zealand is probably the DNDC (DeNitrification-DeComposition) model (Li et al. 1992; Saggar et al. 2004, 2007b). This is a process-based model which can describe simultaneously emissions of trace-gases, soil carbon sequestration, and plant yield. Developed in the United States, the model has been adapted to the New Zealand conditions and has already been used in some studies (Giltrap et al. 2007; Saggar et al. 2007a). Other tools available for modelling gaseous losses include DayCent (Stehfest & Müller 2004), WNMM (Li et al. 2007b), and the use of Automated Neural Networks (Ryan et al. 2004).

There are also several researchers in New Zealand who have developed their own modelling tools, generally for some quite specific job or research project. Some of the approaches taken may be similar to the models discussed above. Other models, however, have been built because of the lack of flexibility or some specific capability in the various existing tools. Some of these models may be of interest in the near feature, especially with regard to risk analysis. These include models built with a probabilistic approach that may include mechanistic description of solute interactions in the soil and also spatial variability due to non-uniform return of nutrient via animal excreta (e.g., White et al. 1998; Shorten & Pleasants 2007; Vogeler et al. 2007; Zhang & Tillman 2007; Wang 2008).

DISCUSSION

There is a wide variety of models able to simulate nutrient balances in New Zealand pastoral farms at various scales (Fig. 3). This variety may seem confusing, but it reflects differing background of modellers and the different purposes for the models. Models can be used for a wide range of applications, from research purposes, to environmental or policy assessment, farm management, land-use risk assessment, and project design and evaluation. Thus, knowing their strengths and limitations is important to select the appropriate tool and ensure correct usage. It is important to note that models are simplified descriptions of the natural systems and all models have shortcomings. Model performance is often limited because of incomplete knowledge of the system or processes and due to assumptions, explicit and implicit, made by the modeller (Beven 2002; Hojberg & Refsgaard 2005; Council for Regulatory Environmental Modeling 2008). Therefore, uncertainties always exist in all modelling efforts.

While the issue of how to deal with model uncertainty is under active development, it is often neglected by developers and users (Pappenberger & Beven 2006; Refsgaard et al. 2006; Brown & Heuvelink 2007; Lowell 2007). The system being described can be itself highly variable. Also, measurement procedures to obtain the data used in the model development and validation are an inevitable source of uncertainty. For example, it is common to compare simulated N leaching against measurements, but all measurements of leaching at any relevant scale are exceedingly variable whenever the experimental methodology has included replication (Addiscott 1996; Refsgaard et al. 1999; Pakrou & Dillon 2004). Therefore, large uncertainties associated with the output are unavoidable when modelling such process.

The variability of many environmental processes is related to the spatio-temporal scale at which they are described. For example, long-term averages of large areas tend to present considerably less variation than a single point on a daily basis. The intuitive step of increasing the level of detail of a model seeking for a reduction of the prediction uncertainties may not yield the expected result. Increasing the model detail can also make gathering the appropriate parameters more difficult, and may as a result introduce more uncertainty into the model estimates. The use of unreliable parameters and input data is regarded as the major source of uncertainty in modelling (Addiscott & Tuck 2001; de Vries et al. 2003; Schoups & Hopmans 2006). Well calibrated process-oriented models are expected to present small uncertainties at small scales. However, the high specificity of these models and the large variability of the processes modelled tend to amplify the uncertainties when increasing the scale (Addiscott 1995; Schlecht & Hiernaux 2005; Sarmah et al. 2006). Farm or catchment budgeting models average out most of the variability by targeting the predictions to large areas and time spans and so allowing simpler descriptions of many processes (Kersebaum & Wenkel 1998; Schlecht & Hiernaux 2005).

Models, thus, should not be regarded as correct or incorrect because of the uncertainty level. It is more appropriate to infer *applicable* models for a given set of requisites. That means selecting a model

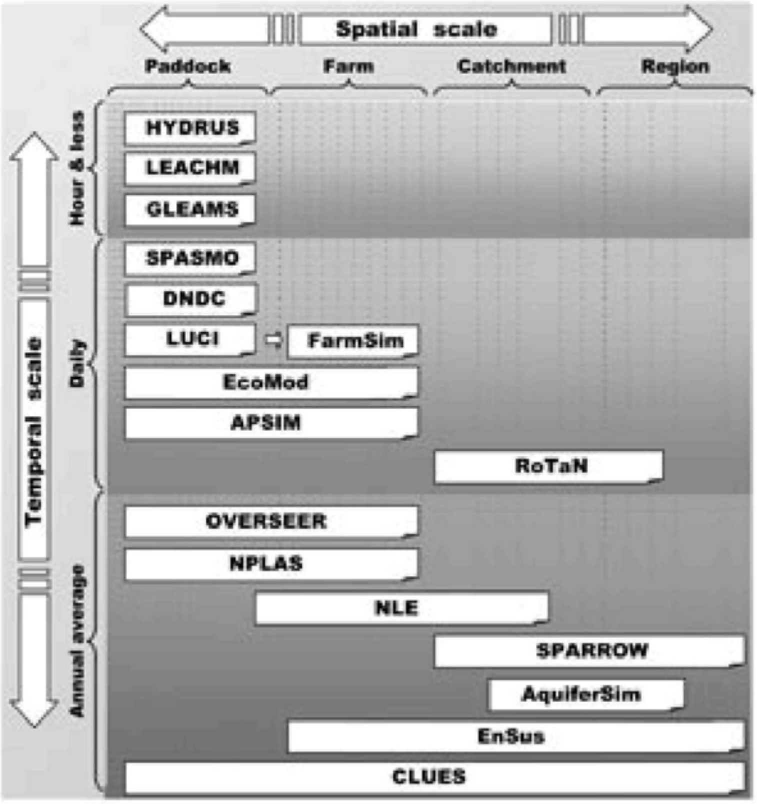

Fig. 3 Distribution of models used for estimating nutrient loss sorted according to temporal and spatial scale.

designed to handle the relevant processes and the possible variations on the management practices at the scale of interest (Rykiel 1996; Scoones & Toulmin 1998; Schlecht & Hiernaux 2005; Cichota & Snow 2008). A compromise might have to be made when choosing or developing a model in order to consider the majority of processes occurring in the system with limited input data. This may imply accepting a higher level of uncertainty.

Nutrient budget models are appealing because of their requirement of a relatively modest amount of input data (Watson & Atkinson 1999; Öborn et al. 2003). However, specific conditions or situations of interest which deviate from the norm or the average might be missed. Models with higher level of detail, such as process-oriented and mechanistic models, may be better suited for such tasks because they can often be set to describe systems with greater specificity. This seems to generally increase the confidence in the model simulations, even though specificity does not necessarily mean greater accuracy. The amount of data required to set up simulations using process-oriented models is a significant limitation of their usage. Also, some degree of expertise is recommended for interpreting the results from these models (Pappenberger & Beven 2006; Lowell 2007).

Models are often better at describing relative differences, such as the increase or reduction of N leaching after a management change, rather than providing the absolute values of leaching. It is important to take this into account when analysing model outputs. Dynamic paddock models and process-oriented soil models can also be useful to derive simpler functions for improving or calibrating the coarser-scale catchment or farm budgeting models. This is an approach which is gaining popularity (Young et al. 1996; Khaither & Erechtchoukova 2007). For instance, upgrades for the crop and horticultural modules of OVERSEER® are being supported by simulations made using process-oriented models, including SPASMO and LUCI (Whiteman & Brown 2009).

In New Zealand, nutrient budgets have been successfully used for supporting fertiliser management for quite a long time and recently have been used as monitoring tools for environmental policy (Ledgard et al. 2004; Dragten & Thorrold 2005; Wheeler et al. 2006; Monaghan et al. 2007). The ability of such models to evaluate management options is quite limited, but increase as models such as OVERSEER® are updated (Wheeler et al. 2006; Wheeler 2009). Process oriented models are also gaining popularity and their use is likely to increase. They have been applied in several research studies and more recently have been used to identify causes for nutrient loss and mitigation strategies at paddock level (Mahmood et al. 2002; Lilburne et al. 2003; Rosen et al. 2005; Bryant et al. 2007; Green et al. 2007). Likewise, sources and pathways for nutrient discharge into large water bodies and the groundwater have been assessed using modelling (Alexander et al. 2002b; Elliott et al. 2005; Rutherford 2005; Bidwell & Good 2007). Models, therefore, have shown their usefulness and certainly have a key role to play in the assessment and monitoring of nutrient losses. Their use, when made with discernment, will surely be very constructive for improving farming and environmental standards in New Zealand.

Long-term average type models

OVERSEER® is the only user-friendly model already available and in use in New Zealand with sufficient trained consulting staff prepared to deliver farm-level nutrient budgeting. The model is an appropriate tool for the estimation of N and P balances at farm/paddock level. It uses easily accessible input data and accounts for most of the various farm management practices typical in New Zealand. The OVERSEER® model has shown its usefulness as a decision support tool for fertiliser management, although a more comprehensive and publicly available documentation and some more validation tests could be beneficial. The scientific credibility of OVERSEER® would be enhanced if more information about the model was available (Brown & Bewsell 2008) and such documentation is currently in preparation (D. M. Wheeler, 2008 pers. comm.). Documentation for the other long-term average type model, NPLAS, is also not widely available, because NPLAS is only in a development and testing phase.

The proposal to use OVERSEER® as a tool to support policy decisions and environmental monitoring seems feasible, as such an approach has already been implemented in other countries (Goodlass et al. 2003; Oenema et al. 2003). However the limitations of a budget model for such a task should be acknowledged. Nutrient budgets are very useful for providing a snapshot of the current situation and to start informed debate on actions and policies for tackling environmental issues (Scoones & Toulmin 1998; Goodlass et al. 2003; Gourley et al. 2007). These budgets have lesser ability to distinguish the effects of natural variability and its interactions with management practices, especially at non-steady state and/or non-uniform conditions. Because of this, predictions of future trends resulting from land-use change or climate variation should be made with care (Öborn et al. 2003; Oenema et al. 2003).

Dynamic paddock and farm system models

Of the models in this category, SPASMO has been tested the most under New Zealand conditions and has been used in the widest variety of situations and locations nationwide. It lacks, however, a good user interface and the documentation about it is also scattered. APSIM has had fewer applications in New Zealand, but has been extensively used in Australia and overseas. The documentation is freely available and it has a comprehensive user interface. The other models in this category are still being developed and/or need more validation tests. It should be noted that EcoMod has the most user friendly interface and also is very well documented.

There are clear differences between these models with respect to their background and flexibility. SPASMO has been used mostly for horticulture, EcoMod for pastoral systems, and LUCI and APSIM have primarily been used for cropping systems. This may be relevant when choosing one model, although the basic processes are described similarly in all of them. Most important perhaps is the flexibility for setting up simulations. SPASMO has been used for quite a variety of systems, but it cannot dynamically simulate a whole farm, which is important for pastoral systems. User expertise is required to integrate several individual paddock simulations into a farm-average value. SPASMO also assumes a uniform return of animal excreta to the paddock, ignoring a process that is known to be very important in the leaching process from grazed paddocks (Ball & Ryden 1984; Haynes & Williams 1993; Di et al. 2002; Pleasants et al. 2007). APSIM, being a modular framework, is the tool that offers the most flexibility; there are a great number of modules already available that can be selected and integrated by a powerful management engine (Keating et al. 2003; Holzworth et al. in press). Also, with the implementation of the Common Modelling Protocol (Moore et al. 2007), the development of new modules is open to a broader number of researchers, and their implementation is relatively easy. For instance, the ability of APSIM to simulate pastoral systems has been strengthened by the inclusion of the FarmWi$e (Moore 2001) and EcoMod modules into its modelling framework. A promising future model is the combination of the well-tested and validated soil and nutrient modules in APSIM connected to the equally well-tested pasture modules in EcoMod.

Catchment models

Most of the models presented in this category are of interest for research and management at catchment scale. Users of these models or their results include regional councils and environmental agencies. Although these models are not limited to catchment scales, they have their strength or have been mostly used at such scale.

For land planning and as a policy-making support tool, the CLUES framework and AquiferSim have very attractive features. CLUES is still relatively simple and is able to integrate land use, management practices, and system transfers within a catchment area and beyond. It also provides a summary of results in the form of maps. AquiferSim also is on a similar stand, but while CLUES concentrates on surface water processes, AquiferSim's strength is in simulating groundwater transport. There is clear complementarity between these models, and discussions for cooperation are in progress (L. Lilburne, 2009 pers. comm.). However, both CLUES and AquiferSim are ongoing projects and need further development and testing. Other models from this category, notably SPARROW and EnSus, also work at this level and may be useful for environmental management and policy-making support. ROTAN is under development and, along with NLE, needs to be calibrated to regions other than those they were developed for. Most of these models, however, are not detailed enough to respond to fine variations in the landscape or to changes in farm management.

Soil process models

These models, due to their higher level of complexity, seem to remain applicable mainly for scientific and consulting purposes. Soil process models are very useful to investigate particular processes in the soil in detail and have a significant role in developing and testing simpler models. They can be used for evaluating non-equilibrium systems and also extreme case scenarios. They lack, however, flexibility to account for the integration of varying management practices. In the context of this review, these models can be useful for testing some of the assumptions of coarser-scale models or for developing generic functions for use elsewhere. Specific complex situations that demand a high level of description of the soil profile, such as sharp impeding layers, or the interactions between soil-water flow and plant roots, are also issues to be tackled with these complex models.

CONCLUSIONS

The application of models for nutrient management is already a reality in New Zealand. Whether the estimation of nutrient loss is focused on preventing environmental impact or ensuring high levels of farm productivity, models have already shown their usefulness. A new development gaining momentum is the use of models to establish N management targets, such as fertiliser caps, and to demonstrate compliance with legislation. This increasing use makes it more important to recognise the differences between models. Although overlaps do happen, in general most of the models presented in this review are best applicable to a limited set of problems and at differing scales. Knowing their strengths and deficiencies will help to select models properly and understand better their results.

There is much misunderstanding and lack of information about the potential of existing tools and that may be limiting their use and acceptance. We recommend that model developers disclose more information about the assumptions, purpose and known uncertainties of their models. It is important to maintain the development and testing of these models, as well as the studies on the actual processes involved on nutrient loss, so that the descriptions can be better understood and improved. How we communicate and deal with uncertainty, whether arising from measurements or from modelling, is a challenge that deserves a close look in the near future. With a discerning approach and more reliable outputs we will be able to reach wiser decisions.

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