Spatial & temporal modelling of nutrient flows in Australian dairy catchments: Implications for water quality impact assessments in complex landuse mosaics

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ABSTRACT

Considerable resources have recently been invested in projects that have investigated the actual and potential economic, social and, particularly, environmental impacts of land management activities in a "catchment context". These activities have resulted in the development of a much-improved understanding of the likely impacts of changed management practices within the farms and regions in which they were investigated, as well as the development of a number of conceptual models which place individual land uses within this catchment context. The research reported here has transformed conceptual models of dairy farm nutrient management and transport processes into a more temporally and spatially dynamic model. This has been loaded with catchment-specific data and used as a "policy support tool" to allow examination of the potential farm and catchment-scale impacts of varying dairy farm management practices, and of changing the landuse mosaic within some key Australian farming regions. Scenarios were examined ranging from simple, on-farm riparian management and changes in fertiliser use, to gross changes in land use. The results indicate that whilst implementation of environmental best practices can go some way towards reaching water quality targets, the effectiveness of most of these practices is limited. Changes to actual nutrient input rates have the most impact at both the farm and catchment scales, but these improvements come at a considerable cost to dairy productivity. Furthermore, because dairying occupies only a small percentage of the catchments investigated, changes to other land uses within the catchment, or changes to the regional landuse mosaic affect downstream water quality response much more than can be achieved by changes to dairy farm management practices alone.

KEY WORDS: *System Dynamics; modelling; dairy; nutrient management; phosphorus; catchment management.*

INTRODUCTION

Catchment water quality signatures and nutrient loads are significantly affected simply by the areal size of a monitored catchment and the combined effects of the wide range of land uses which generally comprise the overall land use mosaic (Dougherty *et al.,* 2004; Barlow *et al.,* 2007). These factors make it difficult to correctly attribute water quality impacts to either specific land uses or intra-land use land management practices, or to context the impacts of the different, individual management practices or land uses. Together with a number of partner organisations, the Australian dairy industry has recently completed considerable work on assessing the impacts of various farm management practices within Australian dairy farming systems and on the development of conceptual models which describe the relationships between on-farm management practices and subsequent water and nutrient fluxes within dairy farms as well as in the broader catchment environment (Melland *et al.,* 2007; Gourley *et al.,* 2010).

The work described in this paper develops these conceptual models into scientifically-robust dynamic models which can be used to provide numerical and visual illustrations of the impacts of various management scenarios within the broader, dairy farming context and within realistic land use mosaics.

Input data availability regarding land use, farm nutrient utilisation and management practice was more extensive and comprehensive with regards to Phosphorus (P), and so the model discussed in this paper focuses more on this nutrient than on Nitrogen (N), for which this information is less clear. However, the model may be thought of as a "nutrient management" model as many of the practices which have been specifically developed for P-management apply similarly to N.

Modelling assumptions and limitations

There are a number of important assumptions which are implicit in the philosophy behind the design of this model, all of which determine the model structure, proposed uses and limitations at least as much as the quality of data used to populate the model sectors. (Adapted from Freebairn & Rattray, 2008).

- A model is a simplification of reality intended to promote understanding. It is recognised that however complex the model, it will still only be a simplified representation of the real system it is designed to model.
- The easier the model or decision support tool is to use, the more chance it has of being used.
- However, the easier the model or decision support tool is to use, the more chances there are that it could be misused or misinterpreted.
- Model complexity should match the question being answered.

Any model which attempts to mimic a natural system will, by definition, not truly replicate that system, however simple the actual system is. When a system as complex as water and nutrient movement through fields, farms, drains and sediments ranging in scale from a few metres to hundreds or even thousands of hectares is attempted, then the true system complexity is extremely large and is almost impossible to mimic in its entirety.

Overall, it is also important to note that this model has been designed at the dairy "industry" level and, while there is a great deal of detail in the farm component of the model, the model has not been specifically developed as a tool for investigating small-scale changes to farm management within individual farms. It is rather a "policy support tool" which is to be used to test various Best Management Practice (BMP) implementation scenarios and land use mosaic changes at the gross, catchment, regional or industry level.

METHODS

Farm Management Sector

The model has been developed as a number of interlinked but separate, model sectors which represent the major management sectors in farm to catchment water and nutrient transport. This structure is illustrated schematically in Figure 1.

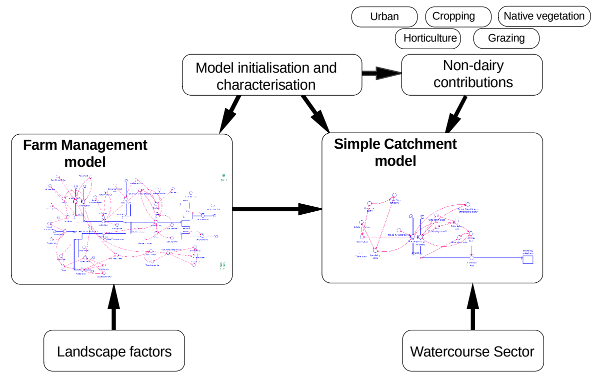

Figure 1. Schematic representation of overall model structure.

Of the 13 distinct model components, the Dairy Farm Management sector and the Catchment sector are the two most complex and extensively developed.

Farm Management Sector

The farm management sector is the most complex sector of the model as it is designed to generically represent the typical physical management structure of an Australian dairy farm whilst also providing the flexibility to describe the wide range of farm practices employed by individual farm managers. Another major reason for the complexity of this sector is that it has been designed to allow the intervention of a variety of currently recommended and best practices within various parts of the farm.

The farm management model calculates P transport on a "per hectare of dairy farm" basis and assumes that all dairy farms within the catchment are adequately represented by this farm structure. Net P transport is calculated at the end of this sector to represent the total P transport for dairying based on the areal and proportional extent of dairying in the catchment. This principal is also applied to the other land uses to calculate their catchment-scale P-transport characteristics although the P-loadings of these other land uses is based on published, areal nutrient export rates and is not calculated within the model by any complicated "in-farm" components as is undertaken for dairying.

A simplified, non-dynamic version of P flow through the farm management model structure is shown in Figure 2. This shows the productive use of P in the farm system in a linear manner but does not show the complex losses, storages and feedback loops which are included in the model but not shown here due to manuscript limitations. Phosphorus essentially enters the model primarily as fertiliser onto the farm paddocks or as feed directly into the dairy herd. It is then transported through the farm system by the herd until it leaves this component of the model as milk or meat or as a loss from the various farm sections into the "catchment".

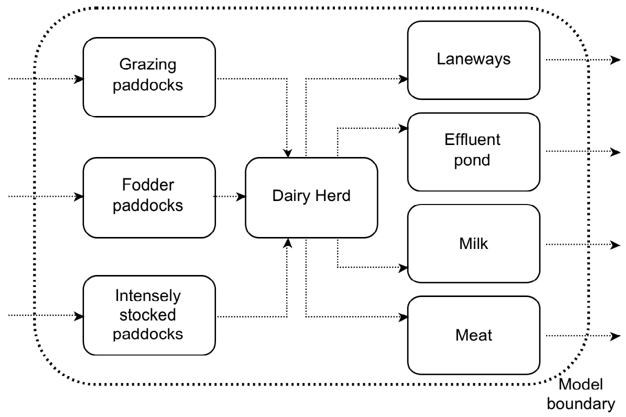

Figure 2. Simplified representation of nutrient movement through Farm Management Sector.

Simplified Catchment Sector

The simplified catchment model sector receives P from the dairy farm sector and also the non-dairy land use components in the model and then routes this P through a series of stocks and flows which mimic the post-farm catchment environment. In a similar manner to that undertaken in the farm sector, this sector is established with soil and nutrient characteristics which are validated and calibrated against regional data.

Modelled Scenarios

Following validation and calibration of the model for three key, Australian dairy catchments (the Peel-Harvey Catchment in Western Australia, and the Gippsland and Latrobe Catchments in Victoria – the Latrobe Catchment is a sub-catchment of the Gippsland Catchment) a series of scenarios were tested to gain some understanding of the likely changes to nutrient losses from dairy (and non-dairy) land.

The modelled (BMP) implementation scenarios were:

- Doubling the dairy farm feed input rate – to model a non-fertiliser driven increase in milk production.
- Doubling the dairy farm fertiliser rate – to model a fertiliser-based farm expansion.
- 70% reduction in dairy farm fertiliser rate.
- In-farm, dairy riparian management.
- Regional riparian management (beyond the farm boundary).
- Both farm and regional riparian management.
- Dairy farm "best practice" fertilising.
- Soil amendment of grazing properties (for Peel-Harvey catchment only as this is a currently recommended, but controversial BMP).

- All BMPs implemented wherever possible.

A series of land use change scenarios were also modelled to gain some perspective of the relative catchment impacts of major land use change which is being discussed in some areas such as the Peel-Harvey:

- Area of dairy farming doubled utilizing current beef farming properties.
- Current dairies converted to beef production.
- Doubling of the urban area utilizing current grazing land.
- All grazing properties converted to native vegetation.
- All grazing properties converted to urban.

RESULTS

BMP implementation scenarios

Increasing dairy farm milk production through increasing P inputs

These scenarios were tested to examine the farm productivity and off-farm effects of an attempt to increase milk production through an increase in feed rate and an increase in fertiliser rate. For the increasing feed scenario, the "typical" feed rate was increased from an equivalent of 5.7 kg P ha^{-1} to 10 kg P ha^{-1}, and for the increasing fertiliser scenario, fertiliser P inputs were increased from 17 kg P ha^{-1} to 30 kg P ha^{-1}.

Following the increase in feed inputs, an increase in milk production of 5% was observed over the course of the model run with no consequent increases in off-site nutrient loss. Increasing fertiliser inputs resulted in a much larger increase in milk production (36%), but the increases in off-site nutrient losses were also large with, effectively, a doubling of the nutrient loss rates in all catchments examined.

These scenarios show the effect of alternative strategies to increase milk production by illustrating the various nutrient loss-exposure pathways of the two strategies. An increase in feed inputs effectively provides increased nutritional levels directly to the milk herd, whilst increases in fertiliser inputs simply add more nutrients to an already inefficient fertiliser – soil – plant – animal P-utilisation system. It should be noted however, that both scenarios assume that the milk herd will always respond to an increase in P inputs by producing more milk and this may not always be the case.

70% reduction in dairy farm fertiliser rate.

The principal route for nutrient inputs into farming systems and, therefore, into the catchments of which they are a part, is via imported fertilisers. These nutrients are effectively added to the farm and catchment soil sector, where they are either stored within the soil profile (permanently or temporarily), utilised productively by pasture or fodder plants, or lost from the soil system to the local and regional hydrological systems.

A direct decrease, therefore, in the levels of nutrient imported into farming systems is likely to have significant environmental benefits in terms of reducing nutrient loss rates. There will, however, also be consequent decreases in agricultural productivity that need to be assessed along with any environmental gains.

Reductions in fertiliser P inputs of 70% in the scenarios modelled in this project resulted in reductions in P loss from dairy farmland to the broader environment at the end of the model runs of between 73 and 76% for the catchments examined, but there were also associated reductions in milk production (as measured by milk P) of approximately 33%.

In-farm, dairy riparian management.

The management of internal nutrient transport processes within agricultural properties is often addressed by improved management of riparian vegetation within the farm systems. This often consists of a combination of fencing activities (stock exclusion) and also improved management or replanting of native vegetation communities.

The implementation of improved riparian management practices in the modelled scenarios did not affect milk production, and produced dairy farm nutrient loss reductions of approximately 1% for the Peel-Harvey Catchment and approximately 14% for the Victorian catchments. There are large differences between the regional effectiveness of this intervention method due to variations in hydrological (and, consequently, nutrient) transport pathways between the regions. Water movement within and from farms in the Peel-Harvey region is generally via subsurface flow, while the (generally) heavier-textured soils of the Gippsland catchments allow a higher proportion of overland flow. Consequently, the effectiveness of riparian management is greater in Gippsland as riparian management predominantly intercepts nutrients flowing overland.

Regional riparian management (beyond the farm boundary).

The scenario which investigated the effectiveness of managing regional riparian systems (rather than within dairy farms) did not generate changes in milk production or edge-of farm P loss, but produced regional P-loss reductions of 13%, 9% and 5% for the Peel-Harvey, Gippsland and Latrobe catchments respectively. These changes differ from those generated by in-farm riparian management discussed above because of variations in the land use mosaics of the three catchments and the varying hydrologic connectivity of the non-dairy land uses.

Both farm and regional riparian management.

The combination of both in-farm (dairy) and off-farm riparian management was also examined.

Edge-of-farm nutrient loss reductions were maintained, but end-of-catchment nutrient loss reductions of 13%, 24% and 20% were achieved for the Peel-Harvey, Gippsland Lakes and Latrobe catchments respectively.

Dairy farm "best practice" fertilising.

The phrase "Best Practice fertilising" is often used as a catch-all phrase to describe the entire suite of "best practice" management methods that would be employed if all farm activities which relate to fertiliser use were employed. This refers to activities including soil testing, fertiliser choice and application techniques and timing, but in terms of this model, this phrase actually means the real level of implementation of these practices.

For example, if "best practice" fertiliser management were actually employed in the Peel-Harvey catchment, then based on soil test results, many farms would not fertilise for a number of years because they have adequate stores of soil P to maintain their production targets. The effectiveness of "best practice" fertilising in the context of this model means the actual effectiveness of farmers' perception that they are undertaking fertiliser management in the "best" sense.

Implementation of this BMP results in reductions in P loss at the farm gate of approximately 1% for the Peel-Harvey and Gippsland Lakes catchments and 9% for the Latrobe catchment.

Soil amendment of grazing properties.

This scenario was executed for the Peel-Harvey catchment as it is a remediation technique which has been investigated over many years and is now starting to be more widely advocated by State natural resource management agencies. The sandy nature of this catchment means that many nutrient intervention techniques which rely on overland hydraulic flow (such as traditional riparian management) are not effective. In order to address this issue, improved farm management techniques which can actually alter the physical and chemical characteristics of soils and fertilisers have been investigated.

Modelling results indicate that amendment of the soils of the majority of regional grazing properties in the Peel-Harvey catchment (often on the poorest soils) may produce nutrient loss reductions of approximately 30% at the farm gate and 14% (or 32 tonnes of P per annum) at the bottom of the catchment. This BMP does not affect dairy farm performance, but neither is it likely to adversely affect grazing farm performance. The improved in-farm retention of P is actually likely to improve pasture production for grazing cattle.

All BMPs implemented wherever possible.

This scenario investigated the implementation of all dairy-farm BMPs as well as those regional BMPs (regional riparian management) which were widely applicable.

Broadscale BMP implementation may produce farm-scale nutrient loss reductions of 2%, 13% and 17% for the Peel-Harvey, Gippsland and Latrobe catchments respectively for no change to milk production for the Peel-Harvey and Gippsland Lakes catchments and a 2% reduction in milk production in the Latrobe catchment farms. These changes translate into end-of-catchment nutrient loss reductions of 24%, 25% and 25% for the three catchments respectively.

Land use change scenarios

Area of dairy farming doubled utilizing current beef farming properties.

This scenario explored an expansion of the regional dairy industry whereby dairy farming expands two-fold utilizing land which is presently used for grazing. In-farm milk productivity and P-use efficiency is assumed to be the same on an areal or per-farm basis and therefore there are no changes to per-farm milk production, but the regional loss of P from the dairy farm gates to the drainage system and the actual volume of milk double (simply because the area covered by dairy farms doubles). However, because of the complicating factors of dairy vs. grazing nutrient use efficiencies, soil condition, positions with respect to waterways etc. across the different catchments, changes to off-farm nutrient transport characteristics are not as predictable.

The total annual P loss from all farmland varies by -4% (a 4% reduction), 15% (a 15% increase) and 16% for the Peel-Harvey, Gippsland and Latrobe catchments respectively.

The proportional allocations of these losses between dairy and non-dairy land, expressed as a change to the overall catchment load is -3%, -1% and -4% for the three catchments respectively. The increases in P-losses from farmland for Gippsland and Latrobe translate into reductions at the end of the catchment because of the locational characteristics of the new dairy areas, the relative efficiencies of these two land uses and the continuing impact of other land uses.

Current dairies converted to beef production.

Conversely, if the land currently occupied by dairies were converted to beef farms, milk production would cease and overall end-of-catchment P loads would vary by 3%, -24% and 5% for Peel-Harvey, Gippsland and Latrobe respectively.

Doubling of the urban area utilizing current grazing land.

Urban expansion into agricultural land is a problem experienced to varying degrees in all modelled catchments but especially in the Peel-Harvey catchment where peri-urban / agricultural conflicts are most apparent. This scenario examined the effect of an expanding urban land component, essentially to develop some context around changes to the dairy industry when viewed in light of changes to other regional “industries”.

Increases in the catchment nutrient load are experienced by all modelled catchments: 17%, 2% and 9% for the Peel-Harvey, Gippsland and Latrobe catchments respectively. These variations between catchments, again, illustrate variations in the original and final land use mosaics.

All grazing properties converted to native vegetation.

Although an unlikely (and unreasonable) scenario, if the land currently used for beef grazing with the catchments was re-planted to native vegetation, perhaps in an effort to try to restore major parts of the catchments to their original condition, then, not surprisingly, following the model run, there are significant improvements in downstream water quality.

The P load to the Peel-Harvey catchment reduces by 22% and the Gippsland and Latrobe catchment loads reduce by 5% and 14% respectively.

All grazing properties converted to urban.

Another unlikely scenario (although more likely in some catchments than the previous scenario) is that grazing properties are all converted to urban land use.

If this were to occur, then the P load to the Peel-Harvey catchment increases by 142% and the Gippsland and Latrobe catchment loads increase by 22% and 68% respectively.

CONCLUSION

The development of this farm-catchment dynamic model has been useful in that specific, detailed scenarios can be run in which the effects of changed practice or land use at a variety of scales can be examined. However, even given the relatively small suite of scenarios run in this exercise and reported here, there are already several more general trends and conclusions which are becoming apparent.

Impact of the current catchment land use mosaic and relative land use impacts

Calibration of the various catchment models executed during this research as well as the execution of the various scenarios has illustrated that there are many more factors than simply the nutrient use efficiency of dairy farms which ultimately affect downstream water quality. For example, it is difficult to attain any real level of catchment-scale improvement in water quality by changes to management of the dairy farms in the Peel-Harvey catchment, simply because these farms, despite their relatively high per-area nutrient loads, only comprise 8% of the entire modelled catchment. Conversely, in this same catchment, because urban areas can have very high nutrient loss rates (up to 50 kg P ha^{-1} year^{-1}), even though they occupy only 6% of the current landscape, their location on very poor soils and adjacent to waterways means that the environmental impact of managing these areas (or expanding them) is high.

The ultimate consequence of modelled changes to land use and management practice is the combination of all of the variations to each land use caused by these changes. If there are any general findings from the suite of scenarios executed here, it is that, end-of-catchment water quality, whilst being affected by all catchment land uses is dominated by the effects of the most significant land use in terms of area. The exception to this rule is that, where high-nutrient loading landuses such as urbanization, are placed in those positions in the landscape where there is little chance for nutrient attenuation processes to occur, then their relative impact will be high.

This is an extremely important point to bear in mind when examining the relative impacts of modifications to dairy farm management practices for any of the three modelled catchments discussed in this report. The Peel-Harvey, Gippsland and Latrobe catchments contain only 8%, 3.7% and 12% dairying respectively, whilst the remainder of their respective catchments are dominated by natural or managed vegetation and grazing land which, in most cases are a number of times larger than that of dairying.

This is not to say that dairy farm nutrient management cannot or should not be improved both for industry efficiency and environmental improvement. Significant improvements in end-of-farm nutrient losses can be attained by better in-farm nutrient management. However, it is clear that improved on-farm nutrient management within land uses which are not spatially dominant and which are located on reasonably well-attenuating soils is unlikely to produce significant catchment-scale improvements in water quality, even in the long term. Conversely, it is likely that improved grazing management practices and better management of urbanisation processes are likely to result in water quality improvements which are observable at the large scale.

The effectiveness of riparian management

As has been observed in the scenario results mentioned previously the impacts on water quality of improved management of the riparian zone can vary greatly both within and off-farm. Riparian management works to improve water quality generally by intercepting overland flow and filtering particulate, water-borne nutrients. Where, however, the regional hydrology is dominated by sub-surface flow, and/or by soluble nutrient forms (such as in the Peel-Harvey catchment), the effectiveness of riparian management at both the farm and regional scales is negligible and this management technique should be questioned in terms of its efficacy if improved water quality is the main goal. Improving the quality of riparian zones may be effective in reducing sediment transport and mobilization, improving landscape amenity, providing shade and creating wildlife corridors, but in terms of improving water quality by intercepting nutrients it is unlikely to be successful. Where, however, overland flow is a dominant hydrological pathway and nutrients are generated in particulate form, riparian management has the potential to significantly improve water quality – at least as long as the health of the riparian zone is maintained.

Expected success rates

Average, maximum off-farm and end-of-catchment, modelled nutrient reductions due to the implementation of improved dairy farm nutrient management and broader riparian management within the present landuse mosaics investigated were around 15% and 25% respectively. These figures were achieved assuming full implementation of all on-farm and regional BMPs and illustrate the water quality improvements that might be expected given full BMP uptake. Notwithstanding the limitations on these conclusions because of their modelled nature, it is clear that catchment water quality improvement targets which are higher than these figures (as most are) will be difficult to achieve under conventional BMP implementation scenarios.

Only by the implementation of less-conventional BMPs (such as soil amendment in the Peel-Harvey catchment) or by significant reductions in catchment nutrient inputs can greater targets expect to be met at the farm gate. However, nutrient input reductions over the long term will incur a productivity cost (although in some instances there will be properties and districts where nutrient inputs can be reduced for some time with no loss in production). For example, reducing dairy fertiliser inputs by 70% in the Gippsland catchment will reduce farm-gate nutrient losses by around 76% and end-of-catchment losses by around 80% but this incurs a loss of milk production of around 33%. Although not modelled in this project, given the greater proportion of grazing land in this catchment, similar nutrient-loss reductions might also be expected if nutrient inputs into grazing properties were also reduced.

This environmental – production relationship illustrates three factors. Firstly: that nutrient inputs and consequent agricultural production levels are closely related; secondly, that it is difficult to maintain agricultural productivity without some adverse environmental impact, and; thirdly, that these relationships needs to be acknowledged by all members of the community. It needs to be recognised that nutrient losses from farms to waterways are caused by the production of goods which are demanded by the broader community and which are produced from natural resource systems that are inherently inefficient in the way they utilise nutrients. Simply put, the production of agricultural products (milk in this case, but not limited to this commodity) requires the import of nutrients into systems which, by their nature, will result in only a 30% input – output efficiency.

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