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Implications of a nitrogen leaching efficiency metric for pasture-based dairy farms

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ABSTRACT

Improvement in nitrogen leaching efficiency (NLE)—the kilograms of milk solids produced per kilogram of nitrogen leached—has been proposed as one strategy to reduce the amount of nitrogen (N) leached from New Zealand dairy farms. A whole-farm optimisation model is used to assess the implications of NLE targets in the Waikato region of New Zealand. In the absence of NLE constraints, there is no relationship between NLE and farm intensification (measured in terms of the proportion of cow diet consisting of imported feed). Indeed, NLE remains stable between 25 kg MS/kg N and 28 kg MS/kg N as a greater amount of imported feed promotes N leaching, but also milk production. In the absence of a stand-off pad (a bark-covered loafing pad employed to reduce urine deposition on pasture), fixing higher levels of NLE decreases N leaching, but imposes an enormous cost on producers by encouraging higher levels of production through the purchase of costly, low-protein supplementary feed. By comparison, with the availability of a stand-off pad, higher levels of NLE allow reductions in leaching to occur at reasonable cost. Nevertheless, levels of N leaching varied significantly between simulated farming systems, depending on the level of NLE studied and variability in the economic environment. Indeed, the coarse relationship between N leaching and NLE infers that N leaching could easily increase under a policy that targets NLE, highlighting the general inadequacy of efficiency measurements for environmental regulation.

1. Introduction

The New Zealand dairy industry is expanding, with production more than doubling over the last 20 years in response to high milk prices. However, being predominantly pasture-based, the intensification of dairy farms in this nation has been linked with increasing nutrient emissions to waterways, given that a high proportion of ingested nitrogen (N) is expelled by grazing animals and partially leached (Doole, 2010; Cameron et al., 2013). A diverse range of policy instruments have been assessed for the New Zealand dairy industry, to identify those schemes that manipulate the incentives facing producers such that they explicitly account for their potential off-site impacts (OECD, 2007). Restrictions placed directly on livestock intensity and/or N fertiliser application have been shown to be broadly ineffective, as they do not directly target the relationship between production and nutrient losses in New Zealand dairy systems (Doole, 2010). By comparison, restrictions placed directly on N leaching levels are effective in reducing losses, since they directly target estimated levels of nutrient outflows and thus incentivise the use of mitigation technologies. Nevertheless, the costs to farmers can be high, depending on farm characteristics and the degree of reduction sought (Doole, 2012).

It is widely understood that milk production and profit are closely correlated in these systems, given that milk income is typically around 90–95% of revenue on New Zealand dairy farms (Parker et al., 1997). Statistical evidence suggests that this relationship is weaker than many expect (Silva-Villacorta et al., 2005). However, the need to maximise milk production for a given feed base is still prevalent throughout the industry (Jay, 2007). Accordingly, a strategy proposed to encourage efficient resource use on

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New Zealand dairy farms aims to maintain a high level of nitrogen leaching efficiency (NLE)—defined as the ratio of kilograms of milk solids produced to kilograms of N leached.[1] A higher NLE level thus denotes that more milk is being produced per kg N leached. Setting a limit on NLE within a certain farming region seems a reasonable regulatory strategy, as it infers that a farm is producing more for a given resource base and management strategy (SLURI, 2007). However, the incentives that such a program provides for environmental and profitable management of farming systems is unclear, particularly given the dearth of analysis relating to this issue.

The concept of nutrient use efficiency is loosely defined in agriculture, but is broadly understood to involve producing more output per kilogram of nutrient applied (Zhang and Tillman, 2007), particularly in the context of crop production (Hawkesford and Barraclough, 2011). Increasing nutrient use efficiency can be achieved through improving nutrient uptake efficiency or improving the efficiency with which plants utilise nutrients (related to the capture of nutrients by roots and their consequent use within the plant) (Barraclough et al., 2010). The concept of nitrogen leaching efficiency (NLE) is broadly similar in that it focuses on efficiency also, striving to achieve greater yield for a given amount of nutrient. However, it is distinctly different also, in that it is defined per unit of nutrient leached. Furthermore, in the context of this application, it concerns a farming system based on grazing animals, so all inputs of a single nutrient (e.g. fertiliser, supplement, N fixation by legumes) must be considered, as well as the recycling of this nutrient via animal excreta. Accordingly, partitioning the NLE measure into its constituent parts is non-trivial, relative to nutrient use efficiency measures used in crop production, as there are numerous factors at the farm level that dictate both production and leaching that must be accounted for. This emphasises the need for a farm-level focus and modelling approaches, when performing an analysis of NLE.

The primary objective of this study is to assess the implications of the incentives provided by NLE limits on dairy farms in the Waikato region of New Zealand. A comprehensive nonlinear optimisation model of a pasture-based dairy farm—the Integrated Dairy Enterprise Analysis (IDEA) framework (Doole et al., 2013)—providing a detailed description of many of the key biophysical processes observed within grazing systems is used for this analysis. The IDEA model provides a consistent and integrated framework within which to predict the potential implications of alternative scenarios. This analysis is valuable as NLE has been promoted as a potential instrument to aid the regulation of N leaching within New Zealand (SLURI, 2007), but has not been studied previously. Moreover, it provides insight into the general value of nutrient efficiency measurements for use within nonpoint pollution regulation in grazing systems.

2. Methods

2.1. Description of the IDEA model

This section provides a concise overview of the IDEA model, based on the description presented by Adler et al. (2013) and Doole (2014). Greater detail regarding the model and its validation are provided in Doole et al. (2013).

IDEA identifies the feeding strategy that maximises annual profit. The model is defined over 26 fortnights to provide comprehensive insight into this feeding strategy across a typical management year. There are five primary sources of feed: grazed pasture, grass silage, maize grain, maize silage, and palm kernel expeller. IDEA determines how much of each of these feeds is provided to the cow herd in a given period. Grazed pasture is the primary source of feed in New Zealand dairy systems (Clark et al., 2007). Surplus pasture is ensiled on-farm during periods when feed supply exceeds feed demand, especially in spring. Maize grain, maize silage, and palm kernel expeller are purchased. Nitrogen fertiliser application promotes pasture growth, with the rate and timing of pasture response derived from the decision tree of Zhang and Tillman (2007). Silages, maize grain, and palm kernel expeller complement pasture intake, and losses during harvesting and feeding are accounted for in the model. Moreover, their feeding compromises pasture intake by substitution (replacement of pasture by supplement), to a degree determined by the season, supplement type, cow liveweight, and level of herbage allowance.

New Zealand dairy farms are rotationally grazed, with areas of the farm grazed at high stocking densities (cows/ha) and then rested for periods of 20–100 days depending on the season. Grazing management is guided by observations of residuals (post-harvest pasture biomass levels). The primary set of decision variables that describes the grazing rotation in IDEA determines the area grazed or cut for silage to a given residual in each period. Accounting for the duration of rest since the last grazing and the residuals at the previous and current grazing or cutting events allows management to impact pasture digestibility (and therefore energy content) and growth. A detailed simulation model of pasture dynamics is extended to incorporate the age structure of herbage tissue (Doole and Romera, 2013), and used to compute average pasture growth, digestibility, and protein content as a function of management decisions, based on data for ten individual climate years.

A large number of cow types are defined in IDEA to allow a detailed description of herd structure. Cows on New Zealand dairy farms are typically fed less than they can potentially consume during the year to conserve feed or allow higher stocking rates to be managed. Thus, five levels of intake regulation, in which cow intake during lactation is proportionally lower than potential, are defined in the model to help balance feed demand and supply. Level 1 denotes that cow intake is only limited by her biophysical potential. Levels of 2, 3, 4, 5, and 6 each denotes cows being fed to 90%, 80%, 70%, 60%, and 50% of the Level 1 intake across lactation. There are also four age groups (1, 2, 3, and 4+ lactations), five levels of genetic merit of cows (expressed in terms of potential milk yield), nine alternative calving dates, and seven lactation lengths incorporated in the model. Cows are also defined as standard cows or those that are to be culled after lactation. The total number of these attribute combinations is 17,640 potential cow types, with each solution containing only a limited number based on the objective function of the optimisation and the characteristics of the simulated scenario (e.g. calving date, milk price, level of imported feed).

The details of each attribute combination describing a given discrete cow type is determined in a large optimisation model external to IDEA. This external model is used to compute the potential intake of dry matter, metabolisable energy requirement, liveweight, body condition, and pregnancy rate of each cow type (Doole and Romera, 2013). Cows are described by their liveweight and body condition in each period. The output variables for each cow type for each fortnight are used as an input into IDEA.

The number of cull cows depends on the natural mortality rate, disease rate, and the non-pregnancy rate computed in IDEA. The time after calving at which a cow first starts exhibiting oestrus is based on age and body condition at calving. The empty rate is computed as a function of the number of heats exhibited during the breeding period, which depends on age and changes in cow liveweight before mating. The age structure of the herd is determined in each solution, dependent on the cull rate and the number

[1] Milk solids are the standard measure of milk volume in New Zealand; specifically, it represents the weight of fat and protein within a given volume of milk. Around 8.5% of a kilogram of raw cow's milk in New Zealand typically consists of fat and protein.