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Plants for dairy grazing systems operating under nitrate leaching limits

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Abstract

Regulations that place a limit on the amount of nitrate-nitrogen leaching from agricultural land are currently being developed by Regional Councils throughout New Zealand. These regulations may require substantial reductions in nitrate leaching from current typical dairy farm levels. Notions of the pasture plant ‘ideotype’, which have previously emphasised pasture growth and the intake of digestible nutrients, should now also include characteristics which can reduce the nitrogen surplus in the animal, and, therefore, the amount of nitrogen (N) excreted in urine. Information on the critical external or internal N requirements of candidate pasture species could be used to develop hypotheses regarding future grazed forage systems; currently, there are few data available for this purpose. Recent empirical evidence indicates that diverse pastures incorporating forage herbs such as chicory and plantain can reduce total urinary N load while maintaining similar levels of herbage accumulation to ryegrass-white clover pasture. However, insufficient information is available to identify the mechanisms through which the urinary N reductions occur. This specific knowledge gap needs to be filled. In addition, more information is needed on the general nitrogen nutrition physiology of candidate pasture species for future forage systems.

Keywords: nitrate leaching; urinary N load; pasture species; plant physiology; diverse pastures

Introduction

Nutrient management is the most pressing environmental issue facing dairying today. Regional Councils throughout New Zealand are currently formulating Land and Water Plans that will deliver the Government’s National Policy Statement (NPS) on Freshwater Management. Under the NPS, Regional Councils must ensure that freshwater quality standards are met in rivers and lakes within their jurisdiction. Nitrogen (N) is specifically notified in regional plans because N loads in some rivers or lakes in most regions are already at, or above, levels considered safe for sustainability of freshwater ecosystems and recreational use. In these areas, Land and Water Plans will likely impose limits on the total amount of nitrate-N leaching from agricultural land uses that is permissible per year. For consents to be granted to continue an existing land use, N leaching may need to be reduced well below current ‘typical’ levels, requiring substantial change in management practices on many farms.

In a paper delivered to NZSAP nearly 25 years ago, Hodgson (1990) identified several plant morphological and compositional factors associated with high rates of herbage yield and pasture intake from grazed pastures. These were mainly directed towards grasses, and included: large leaves and erect growth habit to encourage high growth rates; profuse tillering to encourage rapid regrowth after grazing; low structural strength to encourage high intake rates; and specific structural biochemistry and nutrient balance to provide high nutritive value. In the intervening two decades, increased production has remained the main driver for the pasture-based livestock industries in

New Zealand and agronomic research has continued to focus on the plant factors highlighted by Hodgson (1990).

In the New Zealand dairy industry in particular, this has led to a limited range of plants being used: predominantly perennial ryegrass-white clover pastures, with some brassica and maize crops. There has been relatively little use of pure swards or mixtures of alternative legumes such as red clover and lucerne, or forage herbs such as chicory and plantain. With mounting concerns around the poor persistence of perennial ryegrass in some situations (Parsons et al. 2011), the need for improvement in herbage quality in spring and quality and quantity in dry summers (Clark et al. 1996), and growing awareness of the role that plant species may play in reducing the environmental impacts of dairy farming (e.g. Moir et al. 2012), there has been increased interest in the role that alternative plant species could play in future farming systems.

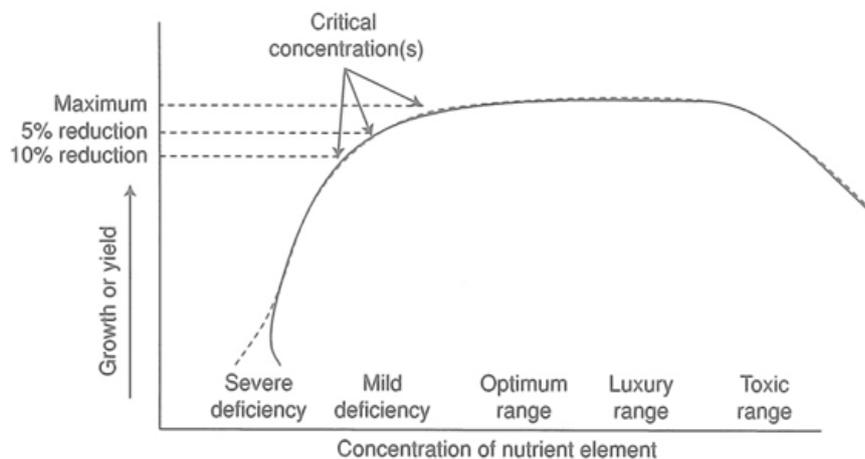
Ultimately, to meet the challenge of reducing nitrate leaching, soil, plant and animal science will need to be harnessed together and integrated with whole systems analysis and development. This paper considers the challenge from a plant perspective. It recognises that the urine patch is the primary source of leached nitrate in pasture-based dairy systems (Di & Cameron 2002), and that the main factor influencing the amount of N excreted in urine is the amount of N consumed by animals relative to the demands of production, maintenance and body tissue retention. Therefore, a logical pathway to controlling N surplus in the animal (the amount of N ingested minus amount required) is to manipulate the N content in the feeds they are eating. In pasture-based production systems,

this is driven by the N content of the pasture consumed and the amount of feed consumed.

Nitrogen in plants and swards

In plants, N exists in several forms: protein (usually the dominant pool), peptides, free amino acids, other organic forms (minor constituents), and inorganic nitrogen such as nitrate and nitrite. N is the critical building block of plant functional enzymes (including rubisco, the major photosynthetic enzyme), and this is the form in which most protein-N is typically found. It is axiomatic that plant growth is restricted when the supply of N in the external environment limits leaf area expansion, enzymatic activity and the rate of carbon assimilation. When the N restriction is removed by adding nutrient, the relationship between rate of N supply and biomass accumulation is typically asymptotic and can be described by a Mitscherlich response function.

Figure 1 General relationship between growth or yield and the concentration of a nutrient element in the plant tissue. From Whitehead (2000).



There are two parameters that can be used to characterise the N nutrition physiology of plants: the critical internal requirement for N (N_{CInt}), and the critical external requirement for N (N_{CExt}). The general concept of critical requirements is depicted in Figure 1 and an example is given in Figure 2. Requirements are determined relative to some percentage of maximum biomass yield: typically 90%. Thus, N_{CInt} is defined as the % N required in dry matter for plants to reach 90% of maximum yield. In the example in Fig. 2 b), N_{CInt} was estimated to be 32 g N/kg DM. Similarly, N_{CExt} is defined by the rate of N supply to the soil medium that is required in order for plants to reach 90% of maximum yield. In the example in Fig. 2 a), N_{CExt} was estimated to be 640 µg N/litre nutrient solution.

Plant species differ in N_{CInt} and N_{CExt} . N_{CInt} is relevant to the nitrate leaching challenge because surplus dietary N will be excreted in urine. A low N concentration at the point when maximum biomass yield is reached should create a more favourable balance between feed supply and total urinary N load

compared with a higher N concentration – provided the maximum biomass yield is similar for both cases. N_{CExt} is relevant to the nitrate leaching challenge because plants with relatively high N_{CExt} require relatively high fertiliser N inputs to reach maximum growth rates. This will increase the amounts of N circulating within the soil-plant-animal system and inevitably increase N losses, including nitrate leaching (Whitehead 2000).

Variation in N_{CInt} reflects variation in characteristics such as relative growth rate (and therefore plant demand for N), photosynthetic capacity, specific leaf area, and the partitioning of N within plants between storage and growth sites. Variation in N_{CExt} is related to factors which influence N capture from soil and re-use within plants, including root morphology, the kinetics of nutrient uptake and transport in plants, and the extent to which nutrients may be stored and recycled within plant organs.

In the case of nitrogen, critical internal and external requirements are linked since the internal requirement for N is met mainly by mass flow in the soil solution when N is in adequate supply. Fast-growing species with a high internal requirement for N will generally have a high N_{CExt} , and vice versa.

N_{CInt} can be determined for individual regrowth events, as shown for four dates of N application in Figure 3. Because conditions for growth vary over time, and plant composition changes as herbage accumulates, N_{CInt} will vary

temporally: the trend shown in Figure 3, across the four N application dates, is for decreasing N_{CInt} with increasing biomass, which is consistent with many published studies (e.g. Greenwood et al. 1990; Justes et al. 1994; Mills et al. 2009). The curve relating N_{CInt} to shoot biomass in Figure 3 is commonly referred to as the N dilution curve, and reflects the increasing ratio of structural plant material (with relatively low N content) to non-structural material (metabolic, with relatively high N content) as biomass accumulates (Greenwood et al. 1990; Belanger & Gastal 2000).

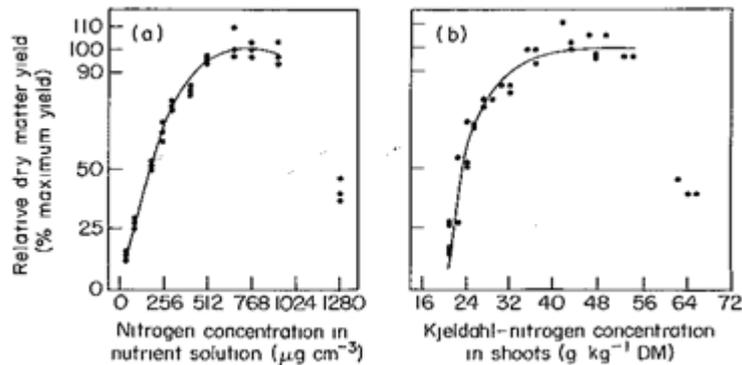
Using data such as shown in Figure 3, Gastal and Durand (2000) proposed a negative exponential relationship between N_{CInt} and biomass:

$$\text{for } C_3 \text{ species, } N_{CInt} = 4.8 \times DM^{-0.34}$$

$$\text{for } C_4 \text{ species, } N_{CInt} = 3.6 \times DM^{-0.34}$$

These equations should be applicable to pasture and forage crop species used in New Zealand pastoral systems. However, their application to growth analysis and nitrogen management of pastures has been limited; the study of Mills et al. (2009) is a notable exception. The Gastal and Durand (2000)

Figure 2 a) effect of increasing concentrations of nitrogen in nutrient solution on relative dry matter yield of ryegrass grown in sand (N_{CExt}); b) relationship between N concentration of shoots and relative dry matter yield of perennial ryegrass (N_{Clnt}). From Smith et al. (1985).

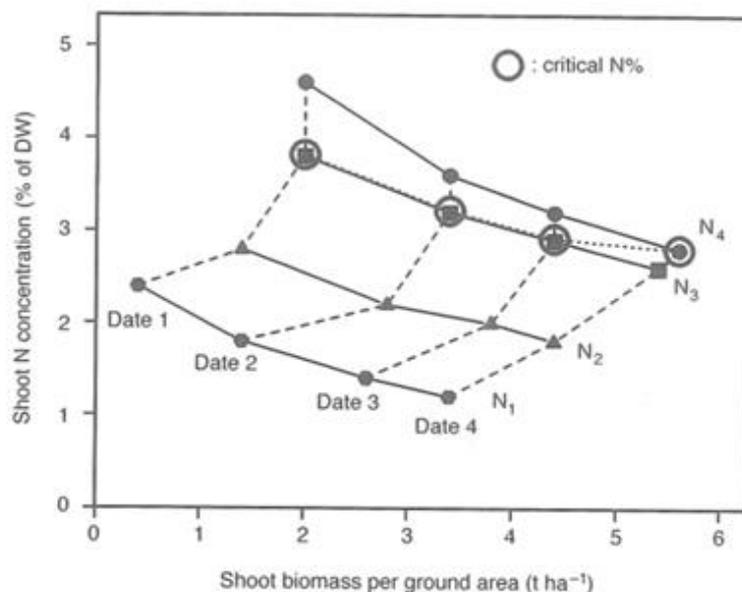


relationships for C_3 and C_4 species differ only in the constant term, confirming the generally-accepted higher N use efficiency of C_4 species compared with C_3 species. Gastal and Durand (2000) state that all species within the C_3 and C_4 functional groups sit on the same relationship. However, N_{Clnt} dilution curves have been shown to be species-specific (Justes et al. 1994), higher in the seedling phase of growth of perennial forage crops (Belanger & Richards 2000), and to decline steadily as perennial forage crops age (Belanger & Ziadi 2008).

Plant/pasture ideotype

Hodgson (1990) used the concept of the plant ideotype to highlight the characteristics required in pasture species for high growth rates and intake. It is

Figure 3 Relationship between biomass accumulation and total N concentration in the canopy of a tall fescue sward grow at four N fertilisation rates. From Gastal and Durand (2000).



timely to re-consider pasture plant ideotypes to include effects on N surplus in animals and nitrate leaching. Plants or pastures with lower N_{Clnt} and N_{CExt} , but similar herbage accumulation rates, compared with perennial ryegrass will improve the balance between feed supply and the potential for N leaching in New Zealand dairy systems. For intensively managed dairy systems, we need to know N_{Clnt} for the point of *maximum average growth rate* during regrowth (or equivalent indicators of optimum time for grazing, for instance in the herbs), not maximum biomass yield because maximum average growth rate (approximated by the '3-leaf stage' indicator) is the point when

feed should be harvested by grazing in a well-managed system. Pastures are seldom, if ever, managed to achieve maximum standing biomass (ceiling yield). Quantifying N_{CExt} is more difficult, especially for swards grown in soil in the field. Nonetheless, comparative information on plant growth responses to variation in N supply is very important, and conspicuously lacking for the range of forage species of interest.

For nitrogen, N_{Clnt} and N_{CExt} are linked and therefore species, or mixtures of species, that reduce one of these parameters will likely move the other parameter in the right direction at the same time. Monocultures are simpler to manage than mixtures, since their botanical composition stays relatively constant and grazing management is not complicated by different plant phenological/physiological requirements. However, mixtures may well be needed to better balance nutrient loss and productivity. There is already proof of concept for diverse pasture mixtures containing herbs, legumes and grasses (Totty et al. 2013; Woodward et al. 2012), though the mechanisms by which they reduce urinary N load have not yet been confirmed.

C-N relationships in plants and swards

Carbon-Nitrogen (C-N) relationships drive herbage accumulation in grazed pastures. Therefore, relationships between processes of C and N assimilation in plants are critical in the search for forages that provide a better balance between feed supply and the potential for nitrate leaching. To address the nitrate leaching challenge through the

use of alternative forages, the effects of variation in N supply on key morphogenetic variables that drive C capture such as leaf appearance and expansion rates, specific leaf area, the mass flux of C and N through swards, and the C and N composition of plants and swards need to be quantified.

Perennial ryegrass provides an excellent example of the need for clear understanding of these inter-relationships. Herbage accumulation rate during regrowth of perennial ryegrass is tightly linked to leaf appearance rates and the number of live leaves per tiller (Parsons et al. 1988, Chapman & Lemaire 1993). To maximise harvest yield, the optimal time to defoliate (graze) is when maximum average growth rate is reached during regrowth (Parsons et al. 1988): this corresponds roughly to the point when the third leaf produced since the last defoliation has fully expanded. After this point, leaf senescence rate increases and net herbage accumulation rate (and therefore the efficiency of growth) begins to decline. Leaf appearance rate in grasses is relatively insensitive to N supply (Belanger & Gastal 2000). The main effect of increasing N supply is to increase the rate of cell division at the base of the leaf, leading to leaves with more cells all expanding at about the same rate as leaves produced under lower rates of N supply (Gastal & Durand 2000). Hence, increased N supply produces larger, but not more, leaves on each tiller. The point when maximum average growth rate is reached during regrowth should be about the same under low and high N supply, and the N content of the leaf (% of DM) will also be about the same since the ratio of cell content: cell wall will be similar. Hence, reducing N supply to ryegrass-based pastures may not substantially reduce the N concentration in the feed of grazing animals (e.g. Shepherd & Lucci 2013). But it will reduce the amount of feed available, and therefore the number of animals that can be sustained per hectare and the total urinary N load returned to the pasture. The latter can be reduced at lower N fertiliser rates, not because of lower N content of the diet, but because of lower C assimilation and feed supply.

Efforts to breed perennial ryegrass cultivars with lower $N_{C_{int}}$ have not been successful (Wilkins et al. 2000); therefore, alternative species need to be considered if our livestock systems are to remain forage-based, but with lower nitrate leaching. There is very little information on the internal C-N relationships of alternative grass, legume or herb species which could be used to predict the effects of changing N supply and management on feed supply and urinary N load of grazing systems based on alternative species. However, there is emerging information indicating that, compared with ryegrass-white clover, mixtures of grasses, legumes and herbs can lead to lower urinary N excretion, and hence less N leaching in dairy systems.

Diverse pastures for managing nitrate leaching

Initial studies on the role of alternative species in dairy systems have focussed on the ability to improve pasture quality, and the seasonality of milk production, often when fed as pure swards. Several studies have noted greater milk production from cows grazing legumes than grasses (e.g. Cosgrove et al. 2001; Nicol & Edwards 2011). The benefits to milk production of including chicory in the diet, as a pure sward in summer, have also been demonstrated (Chapman et al. 2008), reflecting superior nutritive value and higher apparent DM intake compared with perennial ryegrass. However, a concern with some of these species is the seasonality of growth (e.g. low growth rates in early spring), and low overall herbage accumulation, when grown as a pure sward. Yield limitations can be addressed through the use of pure swards of different species grown in separate paddocks and used at different stages of lactation (Woodward et al. 2008) or by combining species in more diverse mixtures (Sanderson et al. 2004).

Recent studies in irrigated pastures in Canterbury (Nobilly et al. 2013) and non-irrigated pastures in Waikato (Woodward et al. 2013) have measured herbage accumulation and botanical composition of binary mixtures of perennial ryegrass and white clover compared to diverse pastures containing additional legume (red clover and lucerne) plus herb (chicory and plantain) species. All pastures were grazed by dairy cows under standard perennial ryegrass-white clover pasture grazing management. In the Canterbury study, herbage accumulation averaged over two years was 10.7% higher in the diverse pastures. Diverse pastures retained a high proportion of herbs after two years, with chicory and plantain making up approximately 40% of the total herbage in the second year. Averaged over two years, metabolisable energy (ME) density was greater in simple than diverse pastures, although the difference was small (12.2 v 12.0 MJ ME/kg DM). Despite the lower ME in diverse pastures, total ME produced per ha was greater in diverse (202 GJ ME/ha/yr) than binary (185 GJ ME/ha/yr) pastures, due to their higher DM production. In the Waikato study, herbage accumulation averaged over three years was similar in binary (15.3 t DM/ha/yr) and diverse (14.7 t DM/ha/yr) pastures, although there were seasonal differences with the diverse mixtures yielding 12% more over summer and autumn in year 2 and 47% more over summer and autumn in year 3, when herbage accumulation was considerably lower than previous years due to a summer drought.

Milksolids production and N excretion in urine have also been compared for late-lactation cows grazing either a standard perennial ryegrass-white clover pasture or a more diverse pasture that also contained chicory and plantain (Totty et al. 2013). The dietary crude protein content of the standard pasture was higher than that of the diverse pasture (26.2 vs 23.7% DM), leading to higher N intake from standard

pastures (610 vs 551 g N/cow/day). Cows on the standard and diverse pastures produced similar milksolids (1.47 vs. 1.49 kg MS/cow/day), but both the N concentration of the urine and estimated total N excretion were lower from cows on the diverse compared with the standard pasture (3.4 g N/l vs 5.8 g N/l; 354 g N/cow/day vs 426 g N/cow/day). In related indoor work (Woodward *et al.* 2012), milk yield and N partitioning to milk, urine and faeces, were compared in dairy cows fed either a standard perennial ryegrass-white clover pasture or a diverse pasture which also contained chicory, plantain and lucerne. The dietary crude protein content of the diverse pasture was lower than that of the standard pasture (15.0 vs 18.6% DM). Milk yield and milk N output were higher in cows fed the diverse compared with the standard pasture (12.5 vs 11.3 kg/cow/day; 79 vs 68 g milk N/cow/day respectively), and total urinary N output from cows fed the diverse pasture was half that of cows fed the standard pasture (100 vs. 200g N/cow/day). This difference is explained almost completely by the difference in total feed N intake (350 vs 466 g N/cow/day) after adjusting for the higher milk N output, and lower faecal N output (136 vs 151 g N/cow/day for diverse and standard pasture respectively) of cows fed diverse pasture.

Further research is needed to determine the mechanisms (forage composition, rumen physiology) leading to a lower N concentration in urine and less N excretion when cows graze diverse pastures containing herbs, and the quantity of herbs in the diet needed to achieve a reduction in N excretion. Diverse pastures containing herbs and legumes may have higher intake potential (Bryant *et al.* 2012); therefore, this work will also need to address how modification of feed allowance and grazing management of diverse pastures may be used to promote greater daily DM intake. This may well lead to greater animal productivity, so allowing stock numbers to be reduced with subsequent reductions in environmental footprint.

Conclusions

In considering the inter-play between the background rate of N supply from soil and fertiliser, the effects of urinary N deposition, and the amount of N consumed and then excreted by grazing animals, the processes of plant N uptake and use must be clearly defined so that the right interventions can be targeted to reduce N leaching losses where required. There is insufficient information for alternative pasture species from which robust analyses of the relationship between feed supply and N balance in pastures can be built. This is a major shortcoming in the knowledge base required to develop more sustainable, pasture-based livestock production systems that meet future requirements for environmental quality.

N fertiliser use is likely to be lower in future farm systems operating under nutrient emissions limits, so this is part of the solution. But we do not know 'how low we can go' with current species (mainly perennial

ryegrass) before the balance tips in favour of other forage species – provided suitable alternatives are available. Some productive forage species/mixtures can reduce total N intake compared with perennial ryegrass/white clover while sustaining similar milk production. Diverse pastures are a good example. However, for the species used in diverse pastures, and for other species, there is an urgent need for comparative information on: plant morphogenetic and herbage accumulation responses to added N measured over multiple regrowth cycles; critical external and internal N requirements; N and C constituents in shoot material; N use efficiency; and the effects of environmental and management variation on these processes.

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