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RESEARCH ARTICLE

Italian ryegrass swards reduce N leaching via greater N uptake and lower drainage over perennial ryegrass cultivars varying in cool season growth rates

Thomas M. R. Maxwell, Roger D. McLenaghen, Grant R. Edwards, Hong J. Di and Keith C. Cameron

Faculty of Agriculture and Life Sciences, Lincoln University, Christchurch, New Zealand

ABSTRACT

Pasture mitigation strategies are needed to reduce the negative effects of nitrate (NO_3^-) leaching from intensive pastoral livestock production systems. We explored the capability of pasture grasses with different cool season (winter–early spring) growth rates to reduce NO_3^- leaching and increase N uptake. Following a single urine application of 700 kg N ha^{-1}, NO_3^- leaching loss and N uptake by Italian ryegrass and four perennial ryegrass cultivars of varying seasonal growth (heading dates from –7 to +20 days), either undersown with/without Italian ryegrass, were quantified in a 12 month lysimeter study. Italian ryegrass cv. Tabu had lower NO_3^-–N leaching loss and drainage, and greater N uptake and DM yield than perennial ryegrass varieties. Italian ryegrass total N leaching loss (143 kg N ha^{-1} yr^{-1}) was 46–33% less ($P < .05$) than early and mid-season maturing Tyson, Arrow and AberDart perennial ryegrass. Italian ryegrass total N uptake (463 kg N ha^{-1}) was 1.2–1.4 times greater than all other grass sward types. Overall, perennial ryegrass pure swards had similar N uptake and N leaching. Late-season maturing One 50 perennial ryegrass showed significantly reduced ($P < .05$) total N leaching loss. Undersowing Italian ryegrass into established perennial ryegrass swards resulted in lower NO_3^- leaching and greater N uptake than non-undersown perennial ryegrass swards, though not significant. Results confirm Italian ryegrass is a useful pasture grass option for reducing annual N leaching loss. Cool season perennial ryegrass varieties appear not to influence soil N uptake and leaching loss.

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Nitrate leaching; N uptake; perennial ryegrass; Italian ryegrass; seasonal growth rate; heading date

Introduction

Elevated nitrate (NO_3^-) leaching from agroecosystems to surface and ground waters is amongst the most serious water pollution problems related to intensified agriculture (Di and Cameron 2002; Mateo-Sagasta and Burke 2010). Growing intensification of grazed livestock production systems is linked to increased outputs of NO_3^- in soil drainage to underground water tables and surface waterways. This can result in water quality deterioration causing detrimental ecosystem and human health effects, such as eutrophic water bodies and excessive NO_3^- levels for safe drinking water (WHO 2007; Cameron et al.

CONTACT Thomas M. R. Maxwell tom.maxwell@lincoln.ac.nz

2013). The prime source of NO_3^- leaching is urine patches of grazing ruminants (Di and Cameron 2016). These localised areas of high N loading onto surface soil exceed the nutrient requirements of pasture (Moir et al. 2011) and lead to NO_3^- loss out of the root zone during periods of soil drainage and low plant N uptake, typically during autumn, winter and early spring (Haynes and Williams 1993; Scholefield et al. 1993; Ledgard et al. 1999). Pastoral livestock production systems are a significant part of the global food system, and sustaining livestock agriculture is important for global food security (Allred et al. 2014). Decoupling productivity from increased environmental pollution is critical to the viability of modern agriculture overall. There is thus great necessity for mitigation techniques that reduce NO_3^- leaching losses from pastoral agriculture.

The strategy of reducing NO_3^- leaching loss from pasture systems by growing combinations of plant species varying in rooting depth and seasonal growth activity resulting in greater uptake of N in the root zone (Vibart et al. 2016) has been demonstrated by Moir et al. (2013), Malcolm et al. (2014, 2015) and Woods et al. (2016). These recent studies revealed the dominant physiological trait of *Lolium multiflorum* Lam. Italian ryegrass/annual ryegrass, specifically greater winter growth (root activity), allowing more N uptake compared with other pasture species commonly grown in temperate grazing systems. To further explore this strategy, we hypothesised that perennial ryegrass *Lolium perenne* L. cultivars with earlier cool season (winter–early spring) growth rates and earlier onset of seed head initiation (heading date) would uptake more N and show lower N leaching than perennial ryegrass cultivars with a later heading date. Heading date indicates when 50% of the growing sward of a grass cultivar have emerged seed heads. The timing is defined relative to the oldest NZ perennial ryegrass cultivar Nui, heading at day 0 (approximately 22 October–mid spring). Heading date is an important trait affecting seasonal production (growth rates and yield), tillering, digestibility and pasture management regimes (Skøt et al. 2005). Ultimately, heading date determines the occurrence of seed head development and the onset of reduced feed quality. In general, an early heading date (up to about +7 days) means better early spring growth while a late heading date means better late spring and summer feed quality (DairyNZ 2017).

The influence of perennial ryegrass heading date on N uptake and N leaching has not been investigated in the context of viable mitigation techniques to reduce N leaching from grazed livestock production systems. This is important because perennial ryegrass is the most widely sown pasture grass species in New Zealand and more long-lived than Italian ryegrass in grazed pasture. In addition, exploring further strategies to reduce N leaching and increase N uptake, NO_3^- leaching and N uptake were measured from established swards of perennial ryegrass undersown with Italian ryegrass. Therefore, the first objective was to determine the effect of pasture grass species differing in cool season growth (pure swards) on NO_3^- leaching loss and N uptake. The second objective was to determine the effect of undersowing Italian ryegrass into established swards of perennial ryegrass cultivars differing in cool season growth (dual-species swards) on NO_3^- leaching loss and N uptake over a 12-month period: i.e. a full pasture-growing season.

Methods

Experimental design, grass treatments, sward establishment and soil properties

Lysimeters were used as the experimental unit for quantifying N uptake and leaching from different grass sward types. Experimental design for the trial was a randomised block with lysimeters of perennial ryegrass cultivar treatments as pure swards or undersown with Italian ryegrass as dual-species swards. A further treatment of pure Italian ryegrass was also used. This provided 9 grass treatments (Italian ryegrass and 4 perennial ryegrass cultivars with or without undersown Italian ryegrass) in 5 replicates (blocks) giving a total of 45 lysimeters. One Italian ryegrass *L. multiflorum* Lam. cultivar (Tabu) and four perennial ryegrass *L. perenne* L. cultivars (Tyson, Arrow, AberDart and One 50) were selected to represent a spectrum of cool season growth, from earlier to later season production and flowering time (heading date).

The Italian ryegrass cultivar Tabu was chosen for its strong winter and spring production compared with perennial ryegrass cultivars (National Forage Variety Trial, New Zealand Plant Breeders Research Association 2016). The perennial ryegrass cultivar Tyson was chosen for its early spring growth habit and very early flowering, having the earliest heading date (−7 days) of commercially available perennial ryegrass cultivars (Agriseeds 2017). Arrow (+7 days) was chosen for its winter to early spring growth habit and medium to late flowering habit (Specialty Seeds 2017). AberDart (+15 days) and One 50 (+20 days) are late-season maturing cultivars, both with later heading dates. One 50 has strong summer, autumn and winter production (National Forage Variety Trial, New Zealand Plant Breeding and Research Association 2016).

Pure pasture grass plots of the various pasture types were established in March 2014 to enable lysimeter collection from the established pastures at a later date. The field site was located at the Lincoln University Research Dairy farm, 15 km south west of Christchurch, New Zealand (43°38′S, 172°28′E). The soil was a free draining Templeton silt loam on sandy loam, a Typic Immature Pallic soil (Hewitt 2010); USDA: Udic Haplustept (Soil Survey Staff 2014) at the Lincoln University Research Dairy farm, 15 km south west of Christchurch, New Zealand (43°38′S, 172°28′E). Soil fertility samples (0–7.5 cm depth) were taken from multiple sites in the grass plots from where lysimeters were collected. Soil fertility levels were: pH (H_2O) 6.1, Olsen P 21 mg L^{-1}, Sulphate-S 14 mg kg^{-1} and a base saturation of 69% (Hill Laboratories, NZ). Two replicate plots of each grass (2.1 × 21 m) were established into a cultivated seedbed using a Flexi-Seeder direct drill. Sowing rates were 20 kg ha^{-1} for perennial ryegrass and 25 kg ha^{-1} for Italian ryegrass. In October 2014, 20% potassic sulphur superphosphate fertiliser was applied at 200 kg ha^{-1} (14.4 kg P ha^{-1}, 20 kg K ha^{-1}, 17.6 kg S ha^{-1}) and lime applied at 2 t ha^{-1}. Grass swards were 9 months old before soil monolith extraction for lysimeter preparation and maintained by irrigation during dry periods, with periodic mowing.

Lysimeter collection, installation and leachate collection and analysis

Large soil monolith lysimeters (500 mm diameter × 700 mm depth) were collected during January 2015 from the pre-established pasture plots following the well-practiced protocols and procedures of Cameron et al. (1992). In summary, a metal casing was placed on the soil surface and the surrounding soil dug out as the metal casing was gradually pushed down to 0.68 m depth. The soil monolith bottom was separated from the soil profile using a cutting plate that was then secured to the metal casing, allowing the soil monolith to be lifted from the soil collection site. Replacing the bottom 0.05 m of the soil monolith with gravel stones created a similar free draining condition to the field. Petroleum jelly was used to seal the gap between the soil core and the metal casing so as to prevent edge-flow effects. The monolith lysimeters were then transported to Lincoln University's lysimeter trench facility at the Field Research Centre, using a trailer fitted with airbag suspension to minimise lysimeter disturbance, and installed at the same level as the surrounding field ground level. Plastic tubing was then connected to each lysimeter base and fed into a 10-L container for leachate collection. Italian ryegrass seed was undersown by hand at 10 kg ha^{-1} into half of the perennial ryegrass lysimeters in March 2015, using a knife to make new drill rows in between the existing drill rows of established perennial ryegrass. All lysimeters received cow urine at the equivalent rate of 700 kg N ha^{-1} applied in late April 2015 (mid-autumn). All the lysimeters received natural rainfall and irrigation as required. Leachate was collected every 200 mL (1.1 mm) of drainage (or on a weekly basis) and analysed to determine nitrate and ammonium concentrations (using flow injection analyser). Total NO_3^- leaching losses over the 12-month period (April 2015–2016) were calculated based on NO_3^- concentrations in collected drainage (leachate) from each lysimeter and the volume of leachate. Grass swards were cut at normal grazing heights (from 3000 kg DM ha^{-1} down to 1500 kg DM ha^{-1}) with the collected herbage analysed to determine DM yield and N content (%) from which N uptake was calculated. Total N uptake over 12 months was calculated based on the N concentration and DM yield of grass herbage periodically harvested from each lysimeter.

Data analysis

To analyse N leaching and N uptake by Italian ryegrass and perennial ryegrass cultivars undersown with or without Italian ryegrass, data were analysed using a general ANOVA structure with perennial ryegrass sward treatments nested within Italian ryegrass undersown treatments. Total NO_3^- leaching losses, average monthly NO_3^- concentrations, total drainage, total and seasonal DM yield, and total and seasonal N uptake by the nine grass treatments were analysed using a nested ANOVA with Genstat (16th edition, VSN International). Least significant differences (LSD) were calculated for multi-treatment comparisons, and standard errors of the means (SEM) were calculated and presented with mean values.

Results

Air temperature and water inputs

Cumulative water inputs, rainfall and irrigation inclusive, averaged 1201 mm over the 12-month study period from 28 April 2015 to 29 April 2016 (Figure 1(a)). Cumulative drainage collected from the lysimeters amounted to an average of 253 mm, with 77% occurring over a 5-month period from late autumn (May), through winter (June, July and August) and into spring (September) (Figure 1(a)). Daily average air temperature ranged from a low of −0.4°C in July 2015 to a high of 24.8°C in February 2016 (Figure 1(b)).

Nitrate leaching losses

Inorganic nitrogen leaching from lysimeters occurred predominantly as nitrate (NO_3− > 86%) with minimal ammonium ($NH_4^+ < 10\%$) and nitrite ($NO_2^- < 5\%$)

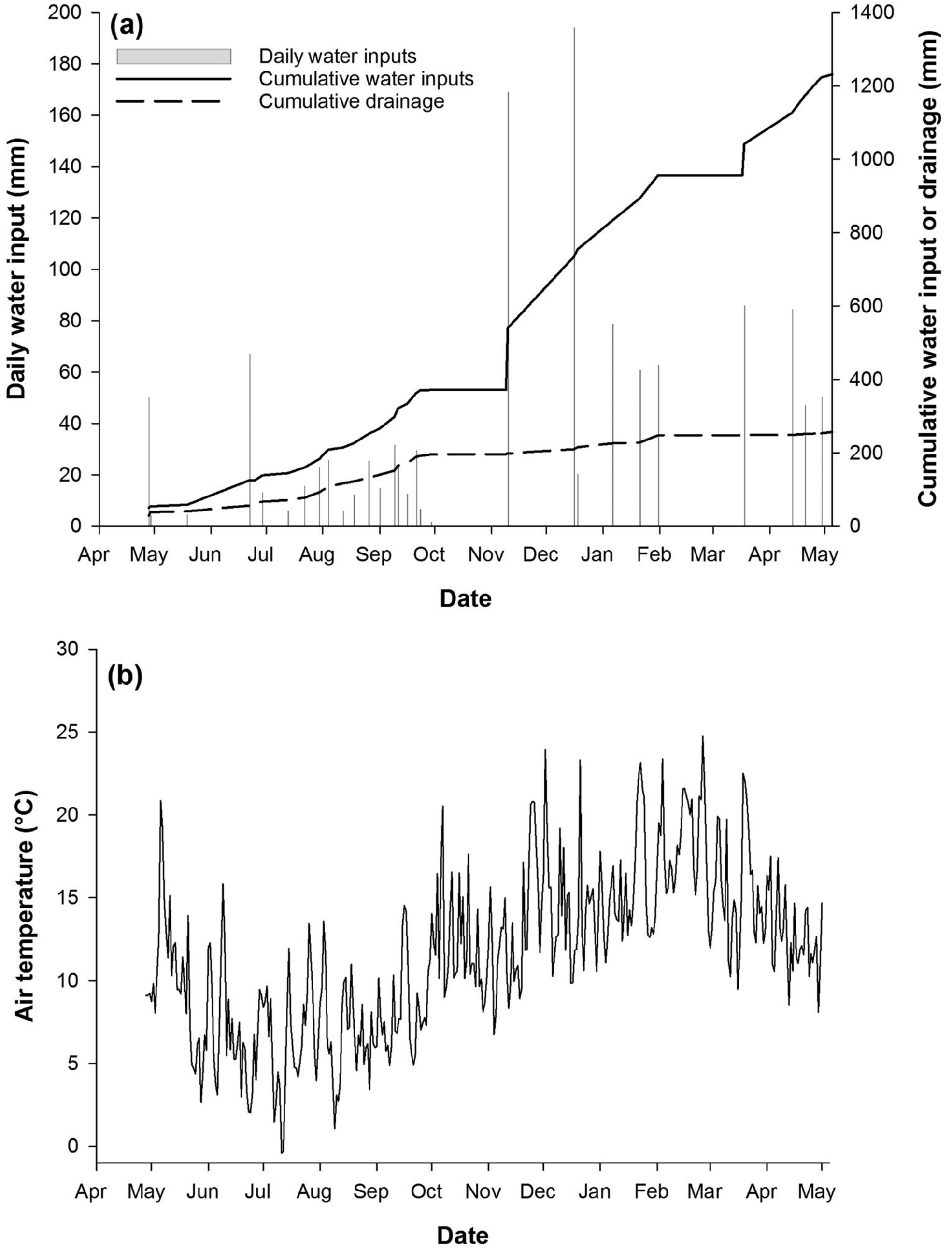


Figure 1. (a) Cumulative water inputs (rainfall + irrigation) to, and cumulative drainage from lysimeters (a) and daily average air temperature (b) for April 2015–April 2016.

present in leachate. For all grass species swards (pure and dual species) the highest concentration (228–119 228 mg NO_3^-–N L^{-1}) occurred in late winter and early spring, with peak NO_3^- concentration occurring in August and September (Figure 2). Overall, the greatest divergence in leachate NO_3^- concentrations between grass swards occurred in August, September and November, spanning the late winter and spring period. Significant differences ($P < .01$) in leachate NO_3^- concentrations only occurred between grass swards in September.

Early spring (September 2015) leachate NO_3^-–N concentrations from pure perennial ryegrass swards ranged from 228 mg NO_3^-–N L^{-1} (Tyson) to 146 mg NO_3^-–N L^{-1} (One 50). The peak Italian ryegrass leachate NO_3^- concentration (119 mg NO_3^-–N L^{-1}) was 29–48% lower than all other sward types and significantly lower ($P < .01$) than the pure and dual-species treatments of Tyson (Figure 2(a)) and AberDart (Figure 2(c)) and the dual-species treatment of Arrow-Italian (Figure 2(b)). Dual-species sward leachate NO_3^-–N concentrations ranged from 180 mg NO_3^-–N L^{-1} (Tyson–Italian) to 135 mg NO_3^-–N L^{-1} (One 50-Italian) (Figure 2). Dual-species swards in general had lower peak NO_3^- concentrations in leachate than pure perennial ryegrass swards during late winter and early spring, although this result was not significant.

Total NO_3^- leaching losses from pure swards ranged from 267 kg N ha^{-1} yr^{-1} (Tyson) to 143 kg N ha^{-1} yr^{-1} (Italian) (Figure 3). Leaching losses from dual-species swards ranged less than pure swards, from 224 kg N ha^{-1} yr^{-1} (Tyson–Italian) to 189 kg N ha^{-1} yr^{-1} (One 50-Italian) (Figure 3). Significant differences in total N loss from leaching were

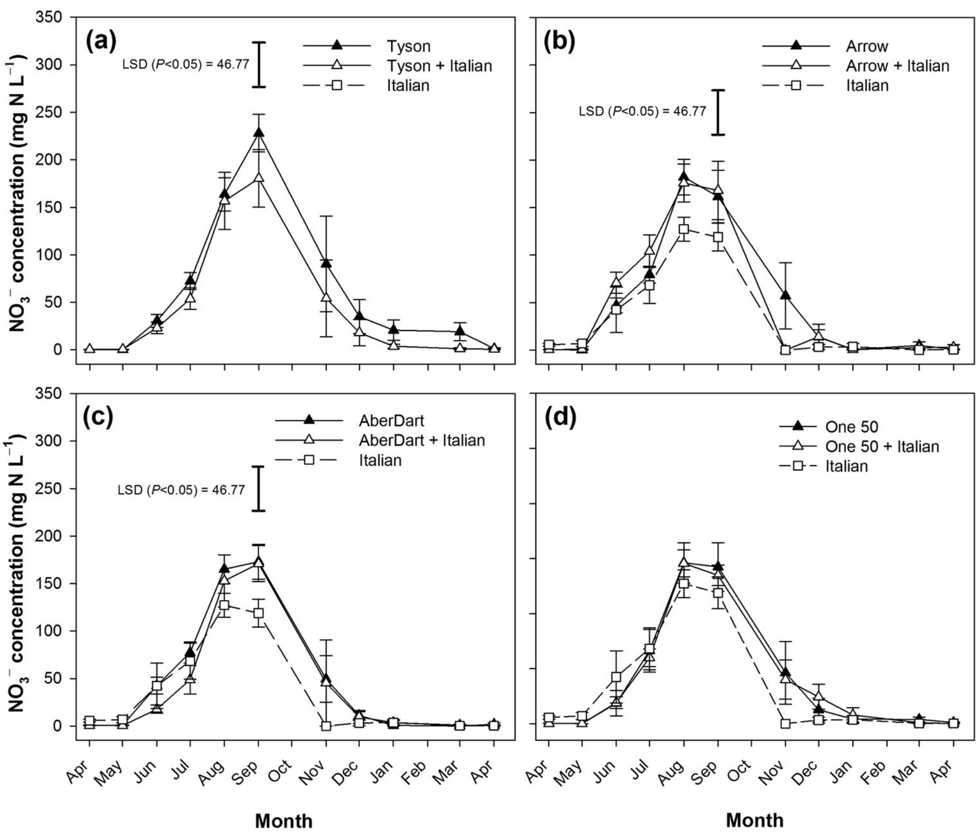


Figure 2. Nitrate-N concentrations in drainage water of pure Italian ryegrass swards and pure perennial ryegrass swards of Tyson (a), Arrow (b), AberDart (c) and One 50 (d) and their undersown Italian ryegrass treatments (dual-species swards). Data are mean values ± SEM ($n = 5$) from April 2015 to April 2016.

evident between sward types. Italian ryegrass (143 kg N ha^{-1} yr^{-1}) leached 46–33% less ($P < .05$) than Tyson, AberDart, Tyson–Italian and Arrow swards (267, 227, 224 and 214 kg N ha^{-1} yr^{-1}, respectively) (Figure 3). However, One 50 perennial ryegrass was the only pure sward type with a total N leaching loss not significantly different from pure Italian ryegrass (Figure 3). The Italian ryegrass NO_3^- leaching loss was 29–19% less but not significantly different from Arrow-Italian, AberDart-Italian, One 50-Italian and One 50 swards (202, 201, 189 and 178 kg N ha^{-1} yr^{-1}, respectively) (Figure 3). Perennial ryegrasses undersown with Italian ryegrass showed an overall trend of reduced total NO_3^- leaching loss for three of the four dual-species treatments compared to pure swards; One 50 was the only pure grass sward to show less leaching than One 50 undersown with Italian (Figure 3), although these differences were not significant.

Drainage

Total leachate volume (cumulative drainage) from pure swards ranged from 308 mm (AberDart) to 165 mm (Italian), while dual-species swards ranged less from 276 mm (One 50-Italian) to 216 mm (Arrow-Italian) (Figure 4). Italian ryegrass produced

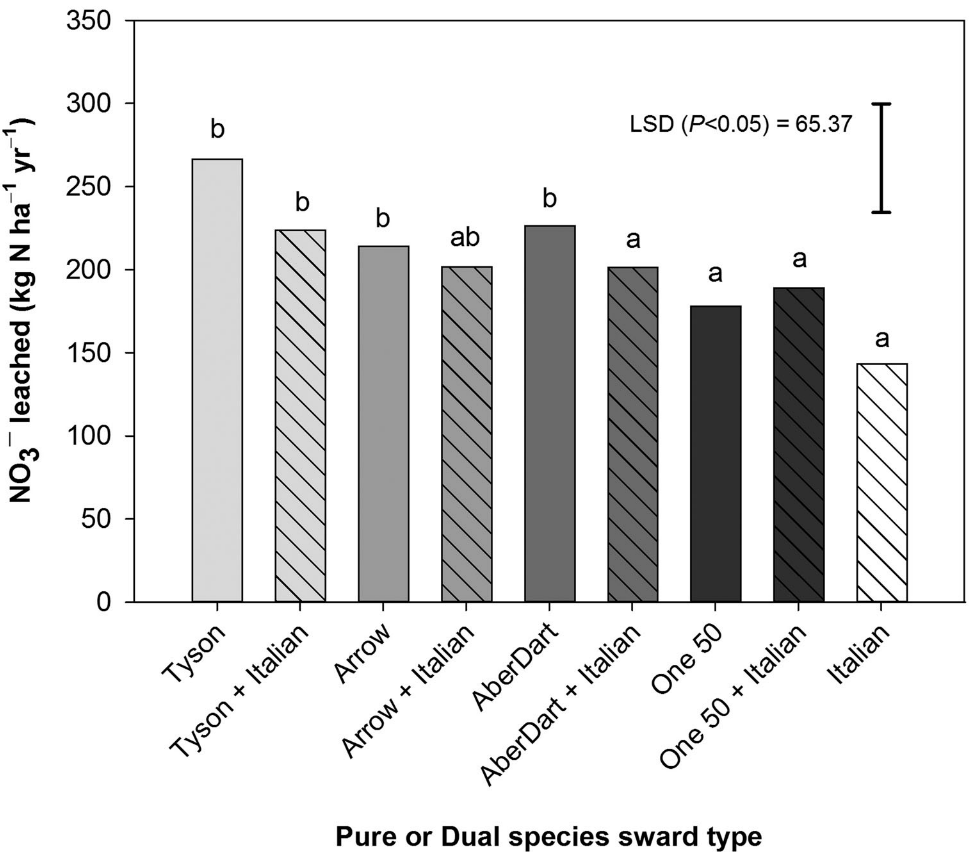


Figure 3. NO_3^-–N leaching losses from lysimeters containing pure and dual-species grass swards differing in seasonal growth rates (heading date): Tyson (−7 days), Arrow (+7 days), AberDart (+15 days), One 50 (+20 days). Data are mean values ($n = 5$) from April 2015–April 2016.

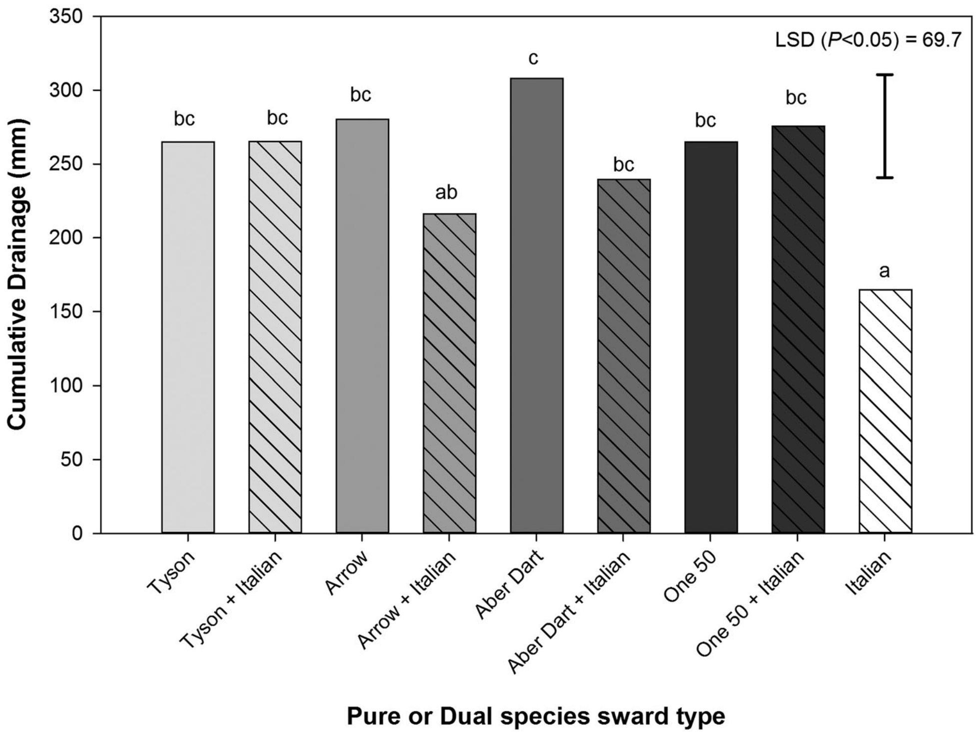


Figure 4. Drainage from lysimeters containing pure and dual-species grass swards differing in seasonal growth rates (heading date): Tyson (−7 days), Arrow (+7 days), AberDart (+15 days), One 50 (+20 days). Data are cumulative mean values ($n = 5$) from April 2015 to April 2016.

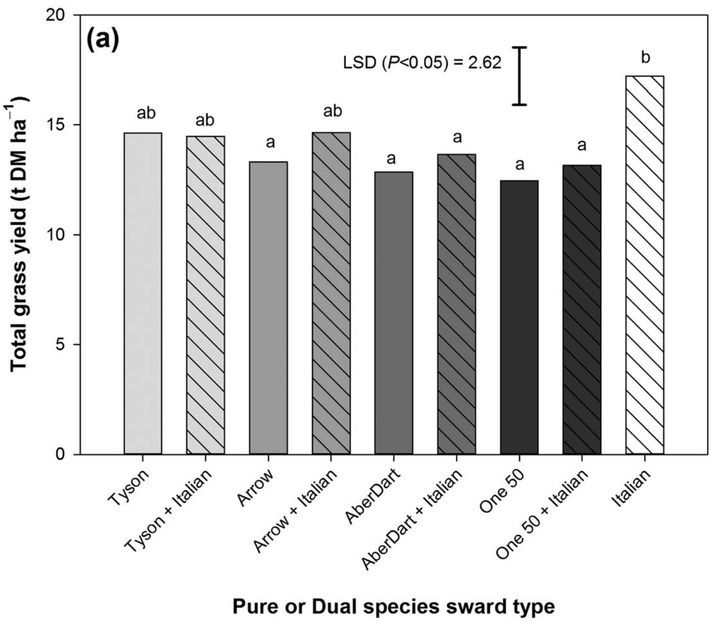
significantly less drainage ($P < .01$), being 46–31% less than all swards except Arrow-Italian (Figure 4).

Yield response and N uptake

Total DM yield of pure swards ranged from 17.2 t DM ha^{-1} (Italian) to 12.5 t DM ha^{-1} (One 50) (Figure 5(a)). Total DM yield of dual-species swards ranged less from 14.7 t DM ha^{-1} (Arrow-Italian) to 13.2 t DM ha^{-1} (One 50-Italian) (Figure 5(a)). Italian ryegrass (17.2 t DM ha^{-1}) was the most productive grass type, generating 1.4–1.2 times more DM ($P < .05$) than most other swards (Figure 5(a)). The total DM yields of the dual Arrow-Italian, pure Tyson and dual Tyson–Italian swards were not significantly less than Italian ryegrass (Figure 5(a)).

Seasonal distribution of DM yields showed all sward types were most productive during spring (October and November 2015) (Figure 5(b)). Pure Italian ryegrass was most productive through the spring period, generating 3.37 and 3.7 t DM ha^{-1} in October and November, respectively (Figure 5(b)). Tyson perennial ryegrass and Tyson–Italian were most productive in October (mid spring), both generating around 2.73 t DM ha^{-1}. Arrow perennial ryegrass and Arrow-Italian showed greatest productivity in November (late spring) generating 2.78 and 3.49 t DM ha^{-1}, respectively (Figure 5(b)).

Total N uptake by pure grass swards ranged between 463 and 331 kg N ha^{-1} and between 372 and 369 kg N ha^{-1} amongst dual-species swards, with greatest N uptake



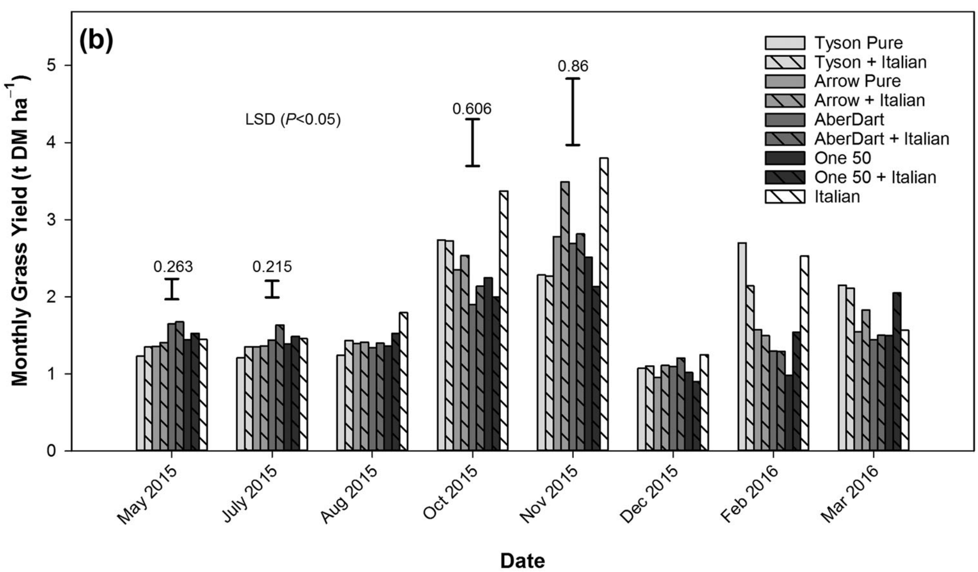


Figure 5. Total pasture dry matter yield (a) and monthly pasture dry matter yield (b) of pure and dual-species grass swards differing in seasonal growth rates (heading date): Tyson (−7 days), Arrow (+7 days), AberDart (+15 days), One 50 (+20 days). Data are mean and cumulative mean values ($n = 5$) from May 2015 to March 2016. A single bold vertical bar above a group of data columns denotes a significant difference in DM yield between grass species on that harvest date.

by Italian ryegrass. Italian ryegrass swards took up 1.2–1.4 times more N ($P < .05$) than any other grass type (Figure 6(a)). Seasonal distribution of sward N uptake showed 60% of total N uptake occurred from late autumn to mid spring (May–October) for all sward types (Figure 6(b)). Italian ryegrass had significantly greater N uptake than all other swards in both late winter (August; $P < .01$) and mid spring (October; $P < .05$) (Figure 6 (b)). Average N concentration of grass herbage ranged from 2.62%N (Tyson) to 3.04%N (Italian), (data not shown). Italian ryegrass herbage contained consistently more N than all other grass swards ($P < .05$) over the 12-month experiment period.

Discussion

The results clearly show the growth of Italian ryegrass has the greatest potential as a mitigation strategy for reducing NO_3^- leaching when compared with the early and mid-season heading date, pure perennial ryegrass swards. This is due to the ability of Italian ryegrass to produce greater DM yield and uptake more N, combined with lower drainage volume and lower NO_3^-–N concentrations in drainage water, leading to the lowest N leaching loss observed amongst the sward types studied. These agronomic traits of Italian ryegrass were most evident in late winter (August) and spring (October) for N uptake, and in spring (October and November) for DM yield.

The results of this study support recent work reporting the general trend of reduced NO_3^- leaching losses and greater N uptake from commercially available Italian ryegrass cultivars compared with perennial ryegrass varieties used in New Zealand pasture systems. Woods et al. (2016) found 35% less N leaching loss from Tabu Italian ryegrass (133 kg N ha^{-1}) compared with a pasture combination of a late heading perennial ryegrass (Expo, +21 days) and white clover (205 kg N ha^{-1}) over a 17-month field-based lysimeter study. Malcolm et al. (2014) found that over two growing seasons, Tabu Italian ryegrass-white clover pasture leached 24–54% less NO_3^- than One 50 perennial ryegrass-white clover, tall fescue-white clover, and a diverse pasture mix containing Italian and perennial ryegrasses, white and red clover, chicory and plantain. In a glasshouse soil column study, Moir et al. (2013) reported lower leaching by *L. multiflorum* annual ryegrass cultivars than two late-season maturing perennial ryegrass cultivars (Alto: +14 days; Aber Magic; +19 days). Feast II and Tama annual ryegrass leached 53% (134 kg N ha^{-1}) and 58% less (130 kg N ha^{-1}) respectively than Alto (280 kg N ha^{-1}) and Aber Magic (310 kg N ha^{-1}) perennial ryegrass. Woods et al. (2016), Malcolm et al. (2014) and Moir et al. (2013) all subjected pastures to a directly comparable N (urine) loading rate to our study of 700 kg N ha^{-1}. The N leaching loss value observed for Italian ryegrass in our study of 143 kg N ha^{-1} yr^{-1} is similar to that observed by Woods et al. (2016) and Moir et al. (2013) for pure *L. multiflorum* Italian/annual ryegrass. The higher leaching loss of 230 kg N ha^{-1} reported by Malcolm et al. (2014) reflects the influence of the pasture legume white clover as a N-fixer, and thus contributor to soil N input and total N leaching over a growing season.

One 50 perennial ryegrass was the only perennial ryegrass cultivar that did not differ significantly in N leaching loss from Italian ryegrass in our study. This is in contrast to the findings of Malcolm et al. (2014) who observed significantly greater N leaching from One 50 perennial ryegrass-white clover pasture than Tabu Italian ryegrass-white clover pasture. The presence of an N-fixing legume species such as white clover growing with One 50 perennial ryegrass as a mixed species sward, may have contributed to the greater nitrate leaching observed over the course of the growing season in the study of Malcolm et al. (2014). This may have been due to lower continuous growth by the legume component and thus less N uptake compared to grass, and increased N in soil coming from the legume component. In our study, the N uptake by One 50 perennial ryegrass (371 kg N ha^{-1} yr^{-1})

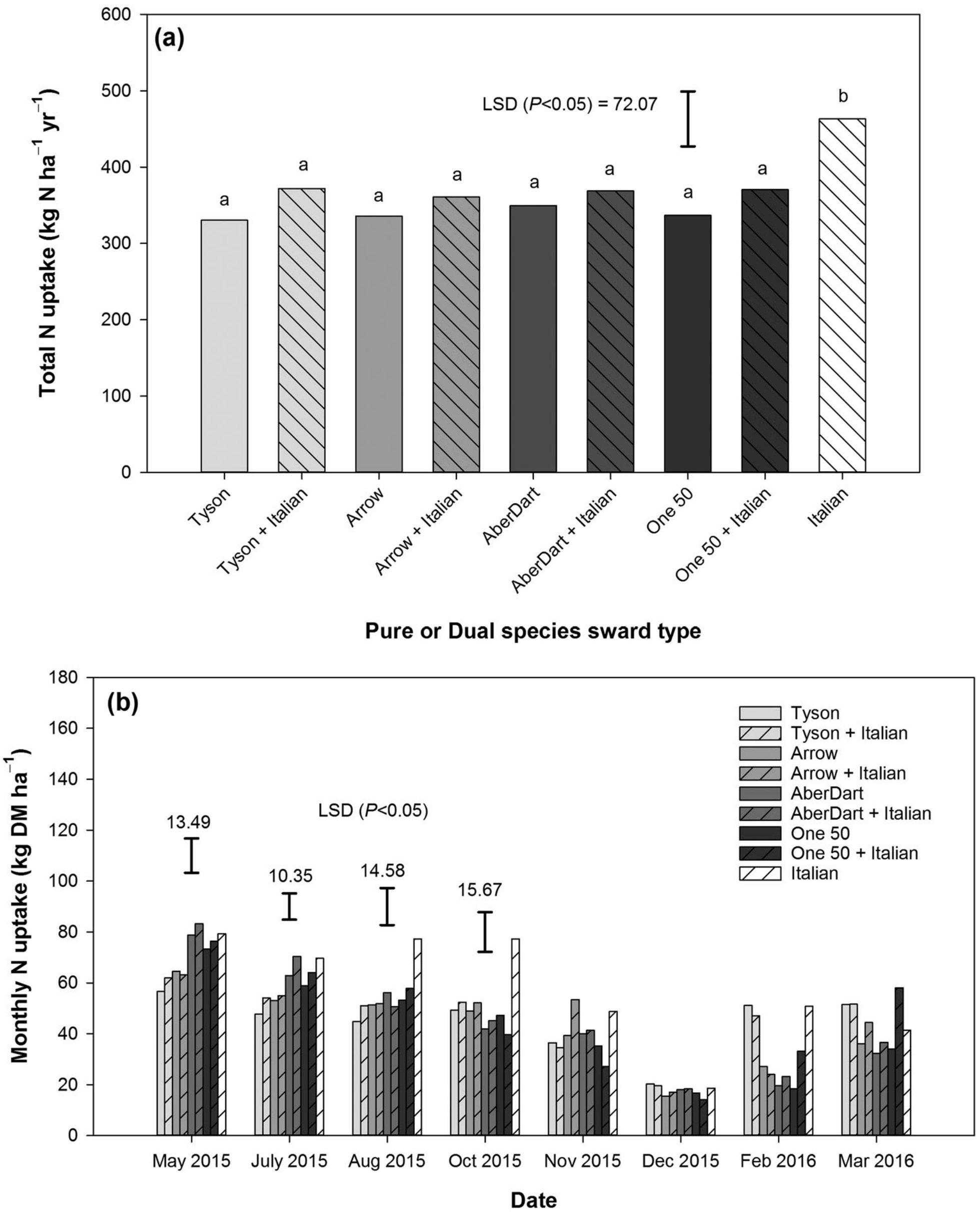


Figure 6. Total N uptake (a) and monthly N uptake (b) by pure and dual-species grass swards differing in seasonal growth rates (heading date): Tyson (−7 days), Arrow (+7 days), AberDart (+15 days), One 50 (+20 days). Data are cumulative mean values ($n = 5$) (total uptake) and mean values ($n = 5$) from May 2015 to March 2016. A single bold vertical bar above a group of data columns denotes a significant difference in N uptake between grass species on that harvest date.

was significantly less than Italian ryegrass (463 kg N ha^{-1} yr^{-1}) and resulted in 46–33% less N leaching by Italian ryegrass. The trend of reduced N leaching loss of Italian ryegrass compared to other pasture mixtures containing perennial ryegrass is also reported by Woods et al. (2016), Malcolm et al. (2014) and Moir et al. (2013).

The Italian ryegrass yield response was 1.2–1.4 times greater than most other grass types. Similarly to our study, Moir et al. (2013) found *L. multiflorum* annual ryegrass (Feast II and Tama) had greater DM yield responses over two late heading date-late-season maturing cultivars of perennial ryegrass, Alto (+14) and Aber Magic (+19). Feast II and Tama annual ryegrass produced 1.9 and 1.8 times more DM than Alto perennial ryegrass, and 1.4 and 1.3 times more DM than Aber Magic perennial ryegrass respectively. The study of Moir et al. (2013) lasted 3 months in contrast to the 12-month duration of our study and used packed soil columns in a glasshouse rather than undisturbed soil monoliths in the field. However, the 90-day trial period of Moir et al. (2013) was designed to represent a typical drainage season for the same geographical area of the Canterbury Plains, NZ. Malcolm et al. (2015) found Italian ryegrass DM yield was 48% greater than tall fescue *Schedonorus phoenix* Scop. syn., *Festuca arundinacea* during a 5-month controlled-climate lysimeter study simulating late autumn–winter–early spring conditions.

Nitrogen uptake by Italian ryegrass in this study (463 kg N ha^{-1} yr^{-1}) was 1.2–1.4 times greater than all perennial ryegrass cultivars, and dual-species grass swards. This result is similar to that observed by Moir et al. (2013) with the N uptake of Tama annual ryegrass (444 kg N ha^{-1}) and Feast II annual ryegrass (484 kg N ha^{-1}) being 1.4–1.5 times greater than Aber Magic perennial ryegrass (322 kg N ha^{-1}) and 1.7–1.9 times greater than Alto perennial ryegrass (254 kg N ha^{-1}). Malcolm et al. (2014) found average winter daily N uptake rate of Italian ryegrass-white clover over two seasons, averaged 58% more than perennial ryegrass-white clover and tall fescue-white clover pastures. Malcolm et al. (2015) found total herbage N uptake by Italian ryegrass was 24% greater than tall fescue. Italian ryegrass showed greater N uptake efficiency (0.48 mg^{-} ^{15}N m^{-1} root) over tall fescue (0.09 mg ^{15}N m^{-1} root). Malcolm et al. (2015) found that tall fescue roots, although reaching deeper in to the soil profile, were relatively inactive during the winter period, adding further support to the greater influence of plant growth over root architecture (deep roots) in recovering soil N and thus ultimately reducing NO_3^- leaching losses. Our results, showing greater DM yield and corresponding greater N uptake by Italian ryegrass during late winter and spring, support the work of Moir et al. (2013) and Malcolm et al. (2014, 2015).

Cumulative drainage volume collected over 12 months from Italian ryegrass was 46–31% less than all the perennial ryegrass cultivars. Further, where Italian ryegrass was undersown in Arrow and AberDart perennial ryegrass swards, cumulative drainage was 22% lower. This is consistent with Nichols and Crush (2007) who found select Italian ryegrass cultivars had 50% less drainage compared with Samson (+3) perennial ryegrass in a 3-month pot trial. Cumulative water inputs and drainage volume results from this study are closely aligned to that observed in previous 12-month field lysimeter studies investigating N leaching loss and N uptake by pasture species from similar sedimentary soil types (Di and Cameron 2005, 2007).

The longevity of Italian ryegrass' effectiveness for mitigating N leaching in temperate pasture grazing systems is limited by its relatively short-lived annual/biennial life cycle. Undersowing Italian ryegrass into existing perennial pasture species mixtures has potential given the reduction in N leaching from the dual-species ryegrass swards in our study, though not statistically significant. Research into how best to integrate and utilise species like Italian ryegrass and plantain *Plantago lanceolata* together into diverse pasture mixtures for maximising environment and productivity benefits for intensive livestock grazing systems would be valuable.

Conclusion

Nitrogen leaching loss, as a function of NO_3^- concentration in drainage water and drainage volume, can be reduced by the use of pasture species with greater N uptake capacity in late winter and early spring. The results of our study indicate that Italian ryegrass and the later heading date and late-season maturing perennial ryegrass cultivar, One 50, are currently the most useful pasture grass options of those tested for reducing N leaching loss over a full 12 month, pasture-growing season. Whereas, the early season maturing/earlier heading date perennial ryegrass varieties do not influence uptake and leaching loss potential of N in soil.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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