Sowing strategy of winter-sown oats catch crops affects crop development and nitrogen uptake

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Abstract

Winter-sown oats are often used as catch crops in New Zealand to reduce the risk of nitrate leaching following grazing of winter forages. Once the crop has been successfully established, promoting fast canopy development should result in quicker nitrogen (N) uptake and further reduce the risk of nitrate leaching. Two field experiments (1 & 2) were conducted in Canterbury, New Zealand, with Milton oats sown under different combinations of target plant population (150, 300 or 450 plants/m^2) and row spacing (75 or 150 mm). Experiment 1 was conducted under simulated urine-patch conditions (urea applied at 400 kg N/ha immediately after planting) in July 2019 and Experiment 2 after winter-grazed kale by non-lactating dairy cows in August 2020. Higher plant population increased aboveground biomass production and N uptake in both experiments. In contrast, tighter row spacing only increased both variables in the first year and for the highest population. Crop canopy cover, represented by normalised difference vegetation index measurements, increased faster with higher plant population in both experiments. There was also evidence that crop canopy cover increased faster with tighter row spacing for the highest plant population treatment in Experiment 1 (urine patch conditions). This study showed that winter-sown oats catch crops could be managed towards higher target plant population ($\geq$300 plants/m^2) to promote biomass production, N uptake and faster canopy development, thus further reducing the risk of N leaching. Sowing in tighter rows could also help to promote these trends; however, it appears more situational, and more evidence is needed to support current findings.

Additional keywords: *Avena sativa*, catch crop, nitrate leaching, inter-row spacing, plant population

Introduction

Nitrogen (N) loss through the process of nitrate leaching following winter grazing is an important environmental issue for New Zealand (Cameron *et al.*, 2013). The Canterbury region has a significant land area used for winter grazing by cattle and a large proportion of this is located on shallow, stony soils and thus can present a significant risk for N leaching.

The use of catch crops has been proven a useful tool for reducing the risk of nitrate leaching during winter and early spring (Fraser *et al.*, 2013; Carey *et al.*, 2016; Teixeira *et al.*, 2016; Malcolm *et al.*, 2018; Thapa *et al.*, 2018). This is because they provide a ground cover to protect the soil and uptake N and water during the high-risk period of winter and early spring. This is when high rainfall and drainage is likely and the soil has high N loading following urine deposition from cattle (Haynes and Williams, 1993). Forage oats (*Avena sativa*) are a suitable catch crop for Canterbury because they: (i) are winter-active; (ii) have a deep rooting system; and (iii) fit well within current farm systems as they can be harvested at different phenological stages to fit in the crop rotation and desired end-use (green chop, whole crop silage, etc.).

Little work has been done on management of catch crops to enhance biomass production and N uptake during the main risk period (winter and early spring). Management practices such as manipulation of plant population and inter-row spacing could be adapted to encourage faster canopy ground cover and, hence, increased biomass production. In turn, this may result in increased N uptake, thus reducing the risk of N leaching.

In this paper, we investigate the effects of different combinations of plant population and inter-row spacing on canopy development, biomass production and N uptake of winter-sown oats. We also discuss the implications for the catch crop context.

Materials and Methods

Two separate experiments were conducted at different sites but with similar treatments, the first in 2019 (Experiment 1) and the second in 2020 (Experiment 2). In both years, the treatments consisted of six factorial combinations of two inter-row spacing (75 or 150 mm) and three plant population targets (150, 300 or 450 plants/m^2). Both experiments were set up as a randomised block design with four replicates.

Experiment 1 setup

Experiment 1 was conducted at The New Zealand Institute for Plant and Food Research Limited in Lincoln, New Zealand (43° 38’S, 172° 30’E), in 2019 under controlled field conditions, i.e. no prior forage crop grazing. Soil at the site was a flat deep, well-drained Templeton silt loam with an available water capacity of 190 mm per m of depth (Jamieson *et al.*, 1995). The site was in perennial ryegrass for three years prior to the experiment. Background soil fertility (0–150 mm) was measured for the general trial area and results are summarised in Table 1. All nutrients were within or above acceptable ranges and unlikely to have limited crop growth and development, though lime was applied in mid-April at the rate of 2 t/ha to raise soil pH.

The site was prepared by ploughing and Cambridge rolling in late April, followed by power harrowing and another Cambridge rolling in mid-June. Base fertiliser was applied in late June and consisted of 250 kg/ha of 30% Potash Super (17 kg P/ha, 37.5 kg K/ha, 18.5 kg S/ha and 37.5 kg Ca/ha).

Following germination assessments, Milton oats were sown on 1 July 2019 by direct drilling in 75 or 150 mm inter-row spacing at 57, 113 and 170 kg seed/ha, corresponding to target populations of 150, 300 and 450 plants/m^2, respectively. The experimental layout was a complete randomised block design. Immediately after sowing, 400 kg N/ha were applied to all plots using Sustain N (coated urea) to simulate animal urine-N deposition (Malcolm *et al.*, 2016). Plots were 10 m long by 13 rows wide (0.975 m for 75 mm row spacing, or 1.95 m for 150 mm row spacing). Following planting, the trial was managed following conventional practice for pests, diseases and weeds.

Experiment 2 setup

Experiment 2 was conducted on a commercial winter support block in Springston, New Zealand (43° 38'S, 172° 21'E), in 2020. This was established to test the same treatment combinations as those in Experiment 1, but over a second season for seasonal comparisons, as well as under a grazed paddock scenario, i.e. 'on-farm'. Soil at the site was a flat shallow Balmoral stony soil. Prior to the experiment, the site had produced 18 t DM/ha of forage kale (*Brassica oleracea*), which was grazed by pregnant non-lactating dairy cattle over the 2020 winter. Over previous seasons (2016–2019), crop rotations alternated between fodder beet and annual ryegrass. Background soil fertility (0–150 mm) was measured for the general trial area and results are summarised in Table 1. All nutrients were within or above acceptable ranges and unlikely to have limited crop growth and development.

The site was prepared in mid- to late-August by discing followed by power harrowing and Cambridge rolling.

Milton oats were sown on 19 August 2020 (49 days later than in Experiment 1) and the experimental layout was a complete randomised block design. Plots were 10 m long by 13 rows wide (0.975 m for 75 mm row spacing, or 1.95 m for 150 mm row spacing). Following planting, the trial was managed following conventional practice for pests, diseases and weeds.

Measurements

Weather data (rainfall, air temperature and global radiation) were recorded via a NIWA weather station located near both trials (43° 37'S, 172° 28'E). Long-term average values of rainfall (1981–2010), mean air temperature (1981–2010) and global radiation (1999–2019) were also collated from the same weather station.

Oats aboveground biomass production was measured at three key growth stages (Zadoks *et al.*, 1974; Tottman and Makepeace, 1979) in both experiments (Table 2). In Experiment 1, this was carried out at GS21 (tillering), GS31 (first node appearance) and GS55 (50% ear emergence). In Experiment 2, measurements occurred at GS21 (tillering), GS32 (second node appearance) and GS37 (flag leaf visible).

For each sampling, a quadrat of 0.4–0.5 m^2 was cut at ground level and the total aboveground fresh biomass weight was recorded. A ≈300 g subsample was then dried at 60°C using a fan-forced oven until a constant weight, then weighed to determine the dry matter (DM) content and calculate the dry biomass yield (DM yield). The subsample was then finely ground and analysed to determine total N content by following the Dumas combustion method and using a LECO CNS-200 analyser (LECO Corporation, St Joseph, MI, USA). Crop N uptake (kg N/ha) was calculated as the product of the DM yield and the N content.

The proportion of crop canopy cover was estimated from reflectance measurements taken every 5–10 days using a Trimble® GreenSeeker® crop sensing system (Trimble Agriculture Division, Colorado, USA). The GreenSeeker is a handheld module that has a light source producing light in the visible red (660 nm) and near infrared (NIR, 770 nm) wavelengths and a sensor recording the amount of reflectance of these wavelengths at the rate of 10 readings per second. These measurements were carried out on a 3-m transect following the rows in each plot and the sensor was positioned approximately 0.6 m above the crop canopy. Average reflectance values from the GreenSeeker were converted into a normalised difference vegetation index (NDVI), which has been previously used to approximate canopy cover (Carlson and Ripley, 1997). As total reflectance values are influenced by the soil, bare soil readings were taken at each measurement date and used to scale NDVI values (Carlson and Ripley, 1997): $NDVI_{scaled} = (NDVI - NDVI_O) / (NDVI_S - NDVI_O)$, where $NDVI_O$ and $NDVI_S$ are the values of NDVI for bare soils and a surface with a fractional ground cover of ≥95% (full canopy cover), respectively. Note that data from 13 September 2019 (Experiment 1) were removed from the analysis once determining these were biased outliers due to a technical issue with the instrument.

Table 1: Background soil fertility (0–150 mm) prior to planting at the trial sites for 2019 (Lincoln) and 2020 (Springston), New Zealand.

Fertility indicator	Average site value 2019	Average site value 2020	Optimum range[1]
pH	5.8	6.3	5.7–6.2
Olsen P (mg/L)	20	53	20–30
Exchangeable K (QT)	6	35	0.30–0.60
Exchangeable Ca (QT)	8	12	5.0–12
Exchangeable Mg (QT)	11	45	0.60–1.2
Exchangeable Na (QT)	6	14	0.0–0.50
Cation Exchange Capacity (me/100 g)		22	12–25

[1] Based on values provided by Hills Laboratories Limited for oats and ryegrass

Table 2: Dates of biomass sampling and corresponding crop growth stages (Tottman and Makepeace, 1979) for each experiment.

Experiment	Date of sampling	Crop growth stage
Experiment 1	13-Sep-2019	GS21 (tillering)
	14-Oct-2019	GS31 (first node appearance)
	18-Nov-2019	GS55 (50% ear emergence)
Experiment 2	15-Oct-2020	GS21 (tillering)
	2-Nov-2020	GS32 (second node appearance)
	9-Nov-2020	GS37 (flag leaf visible)

Analysis

The analysis was carried out in R version 3.6.3 (2020-02-29). The package *lmer* was used to fit all the mixed models except with the Greenseeker data when *lme4* was used. The package *predictmeans* was used to obtain the predicted means and related output.

Each variable was analysed separately using a linear mixed effect model approach. The fixed effects in the models were the treatment (combination of plant population and row spacing) and the date of sampling (date as a factor), plus their interaction. The block is included as a random effect to account for repeated measurement from the same block. The plot is included as a random effect to account for repeated measurements from the same plot. For each variable, model assumptions were checked via standard residual plots. A square root or logarithm transformation was applied when needed. Post-hoc pairwise comparison *p*-values were adjusted using the false discovery rate correction to account for multiple tests.

Results

Weather

Experiment 1

By the end of the trial period, a total of 259 mm of water was received, of which approximately 92% was rainfall. Overall, rainfall for the period was close to long-term averages. Air temperatures reached a low of approximately 3.5°C and a high of 22°C, and were marginally lower than long-term average air temperatures. Daily radiation ranged from 1.7 MJ/m^2 in August to 29 MJ/m^2 in November, averaging 11 MJ/m^2/day. The amount of global radiation during the course of the experiment was similar to the long-term averages.

Experiment 2

By the end of the trial period, a total of 327 mm of water was received, of which approximately 40% was rainfall. Overall, rainfall was notably lower than long-term averages. Air temperatures reached a low of approximately 1°C and a high of 20°C, and were marginally lower than long-term average air temperatures. Daily radiation ranged from 2.9 MJ/m^2 in August to 28 MJ/m^2 in November, averaging 15 MJ/m^2/day. From August until mid-September, radiation amounts were similar to the long-term averages, but greater during the latter part of September before tracking similar to long-term averages again for the remainder of the experiment.

Biomass and nitrogen uptake

Experiment 1

Aboveground dry biomass production (DM yield) and N uptake data from Experiment 1 are summarised in Table 3. Dry biomass yield was affected by interactions between treatment (combination of plant population and inter-row spacing) and date of sampling ($p<0.001$). At the first sampling in mid-September (tillering), DM yield increased with plant population but was not affected by inter-row spacing. It doubled from an average of 0.2 t DM/ha for 150 plants/m^2 to 0.4 t DM/ha for 300 plants/m^2, and then increased to 0.7 t DM/ha for 450 plants/m^2. At the second sampling in mid-October (first node appearance), DM yield was still mostly affected by plant population with averages of 2.7, 3.7 and 4.3 t DM/ha for 150, 300 and 450 plants/m^2, respectively. However, there was only moderate evidence of an effect of inter-row spacing at 300 and 450 plants/m^2, with DM yield increasing with tighter inter-row spacing: from 3.4 to 3.9 t DM/ha and 3.7 to 4.8 t DM/ha for 300 and 450 plants/m^2, respectively. At the final sampling in mid-November (50% ear emergence), the trends were similar to the second sampling but variability was high, as indicated by the confidence intervals (Table 3). The lowest average DM yield of 11.2 t DM/ha was recorded for 300 plants/m^2 and 150 mm inter-row spacing, while the highest average DM yield of 15.8 t DM/ha was recorded for 450 plants/m^2 and 75 mm inter-row spacing. The other treatments produced an average of 12.9 t DM/ha.

Nitrogen uptake was affected by significant interactions between treatment and date of sampling ($p<0.001$). For the first sampling (September), N uptake increased with increasing plant population: by 78% from 150 to 300 plants/m^2, and by 72% from

300 to 450 plants/m^2. At the second sampling, there were similar differences in N uptake between the treatments but the trends were less obvious, as indicated by the 95% confidence intervals. There was also evidence that N uptake was higher with tighter inter-row spacing for the highest plant population of 450 plants/m^2, with an increase of 25% for 75 mm spacing compared with 150 mm spacing. At the final sampling, the differences in N uptake between the treatments were not significant with an average of 304 kg N/ha across all treatments.

Table 3: Total dry biomass production (DM yield, t DM/ha) and nitrogen (N) uptake (kg N/ha) at key crop growth stages (Tottman and Makepeace, 1979) for winter-sown Milton oats using different combinations of plant population target (150, 300 and 450 plants/m^2) and inter-row spacing (150 or 75 mm) at Lincoln, Canterbury, New Zealand in 2019. Means are provided with 95% confidence intervals in brackets.

	DM yield (t DM/ha)			N uptake (kg N/ha)		
Plant population (plants/m^2)	GS21	GS31	GS55	GS21	GS31	GS55
150	0.2 [0.2-0.2]	2.6 [2.1-3.3]	12.1 [9.6-15.2]	13 [10-16]	148 [118-185]	292 [234-365]
	0.2 [0.2-0.3]	2.7 [2.2-3.4]	12.3 [9.8-15.5]	15 [12-19]	153 [123-192]	310 [248-387]
300	0.4 [0.3-0.4]	3.4 [2.7-4.3]	11.2 [8.9-14.1]	24 [19-30]	178 [142-222]	257 [206-322]
	0.4 [0.3-0.5]	3.9 [3.1-4.9]	14.8 [11.8-18.7]	26 [21-33]	211 [169-264]	327 [261-408]
450	0.6 [0.5-0.7]	3.7 [3.0-4.7]	12.5 [10.0-15.8]	38 [31-48]	190 [152-237]	306 [245-382]
	0.7 [0.6-0.9]	4.8 [3.8-6.1]	15.8 [12.6-19.9]	48 [38-60]	237 [190-296]	330 [264-412]

Table 4: Total dry biomass production (DM yield, t DM/ha) and nitrogen (N) uptake (kg N/ha) for winter-sown Milton oats using different combinations of plant population target (150, 300 and 450 plants/m^2) and inter-row spacing (150 or 75 mm) at Springston, Canterbury, New Zealand in 2020. Means are provided with 95% confidence intervals in brackets.

Plant population (plants/m^2)	Row spacing (mm)	DM yield (t DM/ha)			N uptake (kg N/ha)		
		GS21	GS32	GS37	GS21	GS32	GS37
150	150	1.0 [0.8-1.3]	4.0 [3.5-4.6]	6.0 [5.4-6.6]	41 [25-62]	95 [69-126]	109 [81-142]
	75	1.2 [0.9-1.5]	4.4 [3.9-5.0]	6.5 [5.9-7.2]	51 [32-74]	111 [82-143]	122 [92-156]
300	150	1.9 [1.6-2.3]	5.4 [4.8-6.0]	7.6 [6.9-8.4]	73 [51-100]	114 [85-147]	137 [105-173]
	75	1.9 [1.5-2.3]	5.7 [5.1-6.4]	7.2 [6.5-7.9]	73 [50-100]	125 [94-159]	126 [96-161]
450	150	2.3 [1.9-2.7]	6.8 [6.2-7.5]	8.2 [7.5-9.0]	83 [59-112]	147 [114-184]	150 [117-188]
	75	2.3 [1.9-2.7]	6.2 [5.5-6.8]	8.4 [7.7-9.2]	81 [57-109]	130 [99-165]	155 [121-193]

Experiment 2

The DM yield and N uptake data from Experiment 2 are summarised in Table 4. The DM yield was affected by the treatment ($p<0.001$), but there were no interactions with date of sampling ($p=0.793$), which meant that trends were similar for all the samplings. The main factor affecting DM yields was the plant population, with dry biomass production increasing with plant population for all samplings: ranging from 1.1 to 2.3, 4.2 to 6.5, and 6.3 to 8.3 t DM/ha for the first (tillering), second (second node appearance) and final (flag leaf visible) samplings, respectively.

Nitrogen uptake was also affected by the treatment ($p<0.001$), but there were no interactions with date of sampling ($p=0.820$), which meant that trends were similar for all the samplings. Similar to DM yields, N uptake for all samplings increased with plant population. However, the differences were mostly between the low population (150 plants/m^2) and the high population (450 plants/m^2), with 78, 35 and 32% more N uptake measured in the high population treatments at the first, second and final samplings, respectively. Inter-row spacing did not affect N uptake for any of the samplings.

Crop canopy (NDVI)

In Experiment 1, NDVI was affected by interactions between treatment and date of sampling ($p<0.001$). There were no differences in NDVI between the treatments until late August 2019 (Figure 1).

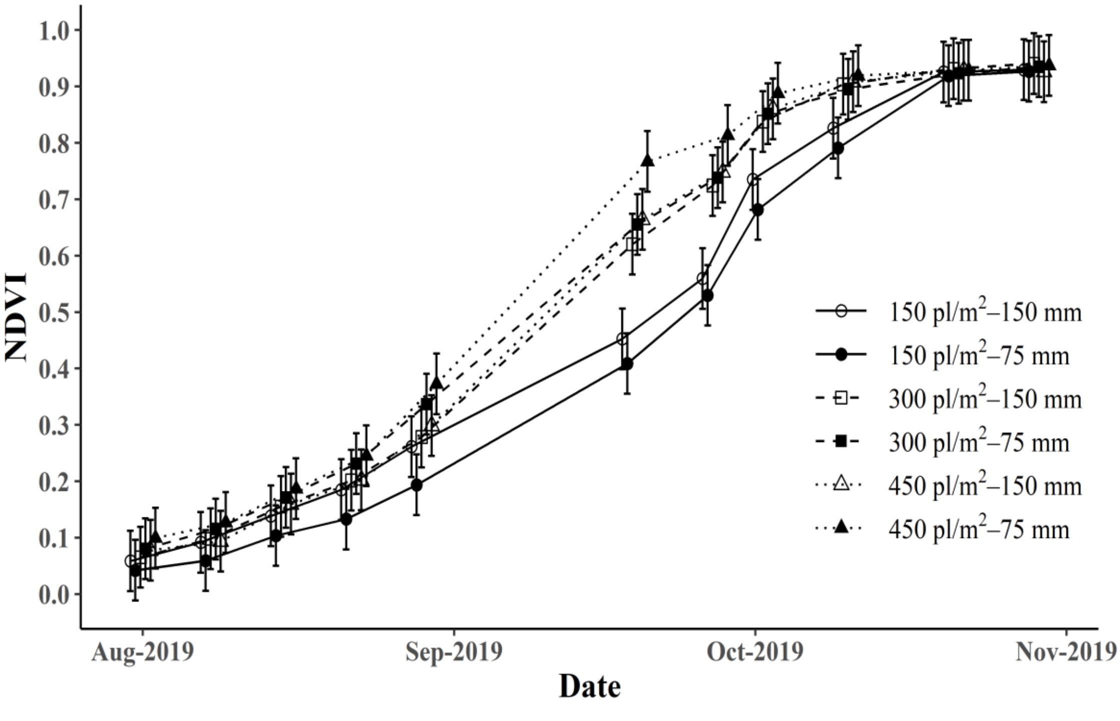

Figure 1: Crop canopy cover (normalised difference vegetation index; NDVI) of winter-sown Milton oats using different combinations of plant population target (150, 300 and 450 plants/m^2) and inter-row spacing (150 or 75 mm) at Lincoln, Canterbury, New Zealand in 2019. Vertical bars represent 95% confidence intervals (bars that do not overlap are considered significantly different at the 5% level).

From 29 August to 21 October 2019, the 150 plants/m^2 and 75 mm inter-row spacing treatment had 10–34% lower NDVI than the higher plant population treatments (300 and 450 plants/m^2). Between 19 September and 10 October 2019, both 150 plants/m^2

treatments had lower NDVI than the higher plant population treatments. From mid-spring onwards (October), differences in NDVI between treatments disappeared as all of them reached full canopy by the end of October. Overall, the 300 and 450 plant/m^2 treatments reached full canopy cover at a similar point in time, while the 150 plants/m^2 treatments were approximately 11–19 days slower at reaching full cover.

In Experiment 2, NDVI was affected by interactions between treatment and date of sampling ($p<0.001$). There were no differences in NDVI between the treatments until late September 2020 (Figure 2). From 21 September until 29 October 2020, the low plant population treatments (both 75 and 150 mm inter-row spacing) had 10–25% lower NDVI compared with the higher population treatments. From 29 September until 17 October 2020, the 300 plants/m^2 treatments had lower NDVI compared with the 450 plants/m^2 treatments. By mid-spring (late October), there were no differences in NDVI between the treatments as they were reaching full canopy. However, as per Experiment 1, the 150 plants/m^2 treatments were notably delayed in reaching full canopy cover, by approximately 12 days.

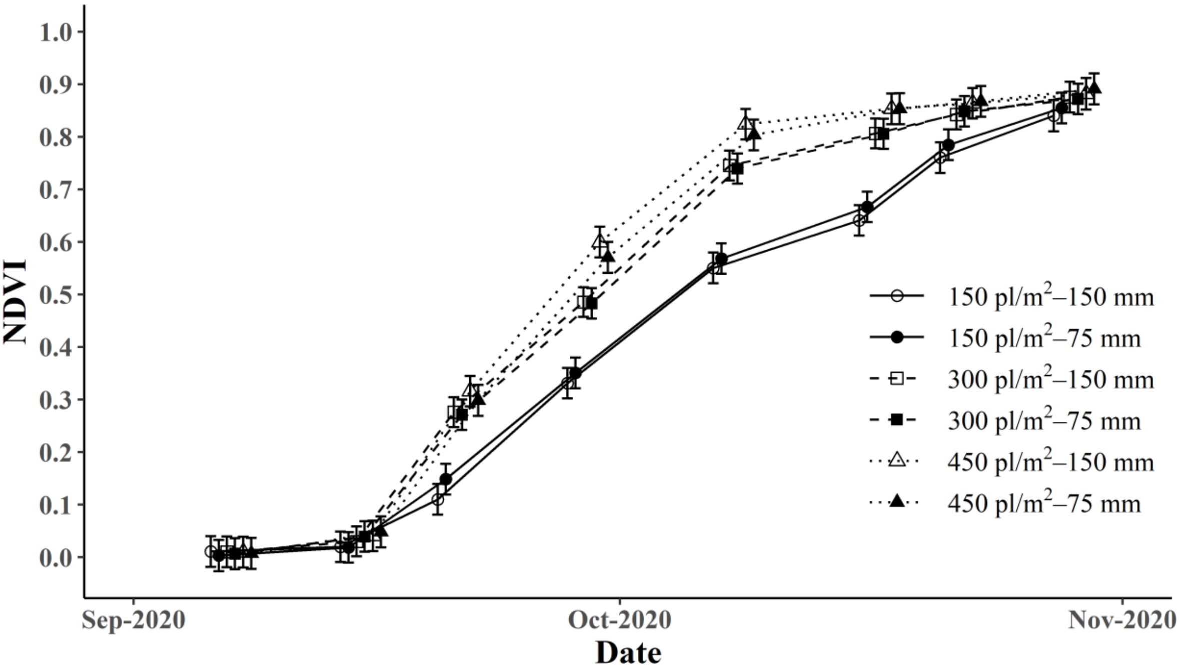

Figure 2: Crop canopy cover (normalised difference vegetation index; NDVI) of winter-sown Milton oats using different combinations of plant population target (150, 300 and 450 plants/m^2) and inter-row spacing (150 or 75 mm) at Springston, Canterbury, New Zealand in 2020. Vertical bars represent 95% confidence intervals (bars that do not overlap are considered significantly different at the 5% level).

Discussion

Plant population was the main factor affecting aboveground biomass production, with biomass production generally increasing with higher target plant population, in both experiments. This trend was supported by the NDVI data, which showed that sowing at higher plant population increased canopy cover faster in late winter and early spring than lower population targets. Those results are also similar to findings from Li *et al.* (2019) with maize. Wu and Ma (2019) found that sowing oat cultivars with an erect-leaf posture, like Milton, at higher plant populations resulted in higher yields because crops with that type of canopy architecture are less prone to lodging. At the initial sampling (x–x t DM/ha), higher plant populations likely resulted in more tillers per unit area, corresponding to higher canopy cover, greater light interception for photosynthesis, and consequently more biomass production on average. At the second sampling (first or second node appearance), when most tillers were still metabolically active, or had just started to senesce, biomass differences previously established were maintained. Although the timing and yields of the final sampling differed between experiments (11.2–15.8 t DM/ha on 18 November 2019, and 6.0–8.4 t DM/ha on 9 November 2020, for Experiments 1 and 2, respectively), biomass production differences across treatments were generally maintained in both cases. This meant that stands in lower population treatments were not able to compensate for the lack of plants, and that inter-plant competition in higher population treatments was not enough to limit biomass production through senescence. This pattern may be due to the nutrient-rich and non-limiting water status of the soil in which the crops were sown, and the catch crop biomass sampling inherently occurring in the vegetative stage of development. Overall, crop development and final yields were in line with those of previous studies considering winter-sown oats catch crops in New Zealand (Yusoff *et al.*, 2013; Malcolm *et al.*, 2018).

In later samplings of Experiment 1, there was also moderate evidence that inter-row spacing influenced biomass production in the 300 and 450 plants/m^2 treatments, with 75 mm row spacing increasing biomass production by 14–32% compared with 150 mm spacing. A study on maize by Barbieri *et al.* (2008) also found that tighter inter-row spacing resulted in higher yields. However, Lukina *et al.* (2000) found no such effect on winter wheat. The increase in dry biomass production in this study is partly supported by the NDVI data, which showed that, for the highest plant population, a tighter row spacing resulted in a faster rate of increase in canopy cover. In addition to the non-limiting nutrient and water status of the soil, this meant that more light was intercepted for photosynthesis, thus increasing biomass production. However, this trend was not observed in Experiment 2, which could be explained by the later sowing of the crop in that experiment (July sowing in 2019 versus August sowing in 2020).

Similar to biomass production, N uptake (the main mechanism by which catch crops reduce N leaching loss) was also affected by plant population in both experiments, and was overall in line with previous winter-sown catch crop study by Malcolm *et al.* (2016). For instance, an increase in plant population resulted in increased N uptake. Similar trends were reported with maize by Li *et al.* (2019). In Experiment 1, this trend was less obvious over time, and, in late spring, there were no differences in N uptake between treatments. In Experiment 2, the trend was maintained until final sampling but the biggest differences were between the lowest and highest plant populations (150 and 450 plants/m^2). There was generally a small or non-significant difference in N uptake between the 300 and 450 plants/m^2 treatments. This means that sowing oats at higher plant populations (≥300 plants/m^2) is likely to help maximise the effectiveness of oats catch crops to reduce the risk of N leaching through increased crop N uptake during the high-risk period in winter and early spring. Once the crop nears the end of its vegetative development, crop N uptake tends to plateau; meaning differences in N uptake between plant populations disappear in late season. This is due to N dilution as biomass increases at later stages of crop development. Furthermore, leaf senescence in late season also limits N uptake as some of it is translocated to other organs or returned as residue. Interestingly, in Experiment 1, there was also evidence that a tighter inter-row spacing resulted in higher N uptake for the highest plant population in early spring. This is a similar trend to that of biomass production and showed that the risk of N leaching could be further reduced at a critical time by sowing the crop in tighter rows.

Gross margins and practical implications

Gross margins and profits were calculated for Experiment 2 and showed that while the highest margins of 919–959 \$/ha were achieved with the highest population target (450 plants/m^2) for both inter-row spacing, the highest profit of 11.6 c/ha of DM was achieved with the 300 plants/m^2 target and 150 mm row spacing.

It is therefore important to ensure high plant populations in order to maximise the environmental performance of catch crops (and in turn, feed production potential). This could be done through careful management (e.g. high seeding rates, achieving good soil-to-seed contact, and adequate sowing depth of 3–4 cm).

However, higher seeding rates may compromise grain yields (if not taken for green-chop or whole crop). Cereal grain crops are typically sown at approximately half the rate. Further research is needed to assess the effects of target plant population on trade-offs between production and environmental performance.

Spreading seeds out through narrower inter-row spacing is likely to result in marginal benefit at particularly high plant populations (e.g. 450 plants/m^2). Computer simulation modelling could be used to assess how widespread this effect might be across various soil types and climates.

Targeting plant populations over 300 plants/m^2 could lead to larger seed shortages, and consequently, more fallow ground or under-performing catch crops where other less effective species have needed to be used.

Conclusion

Overall, these results suggest that agronomic management interventions, such as shifting plant population and row spacing of oats catch crops, can be manipulated to help minimising the risk of N leaching losses to groundwater. A plant population target of 300 plants/m^2 sowed in 150 mm rows likely represents the most suitable target population for cereal catch crops like oats, when considering the likely environmental and productive outcomes, and associated implications of lower or higher plant populations.

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