Determinants of productivity in cropping sequences for dairy systems in Canterbury, New Zealand

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Abstract

The recent expansion of the dairy industry in the South Island, New Zealand, has increased the demand for feed during milking and for over-wintering stock. Theoretical productivity limits for supplementary feeds approaching 45 t DM/ha/annum have been predicted in modelling studies. In this study, we determined practical upper limits for productivity in Lincoln, Canterbury, for 12 cropping sequences in 40 m x 10 m plots under non-limiting soil water and soil fertility. Summer crops consisted of maize, kale and whole-crop barley, and winter crops of oats, Italian ryegrass, forage rape, faba beans and triticale. Highest 2-year accumulated yields of 60.1 t/ha were achieved with maize (hybrid P39G12) as the first crop in the sequence and with a minimum transition period of 36 days. Sequences beginning with kale (cv. 'Gruner') produced up to 53.0 t/ha and those starting with spring barley (cv. 'Salute') yielded up to 49 t/ha. Biomass of individual crops was strongly related to thermal time. However, productivity was best predicted by linear relationships with accumulated PAR intercepted ($r^2>0.995$). Highest yielding crop sequences were achieved with crops with high radiation use efficiency (RUE) and with short transitions between crops. Potential crop losses during crop transitions were calculated from missed full canopy RUE with winter crop production extended into the shoulder season. Highest 2-year potential yield was 70.2 t/ha from maize-wheat-maize-triticale sequence accounting for transition losses.

Key Words

Radiation use efficiency, thermal time, forage crops, transition, dairying, supplements

Introduction

Increased productivity of supplementary feed crops in the South Island will drive the more efficient use of land, provide more feed for lactation and winter feeding, allow increased cow numbers and make dairying more competitive with other land use, and ultimately lead to high returns (DairyNZ 2008). Production of supplements fits well in the pasture renewal phase of pastoral systems (de Ruiter et al. 2009). Recent Australian research has targeted increased forage supply in high input systems with yield targets of 20 t/ha in Victoria (Chapman et al. 2006) and up to 40 t/ha in New South Wales (Garcia et al. 2007). In Canterbury, summer crops with high yield potential include maize, kale and whole crop cereals. Winter crops typically comprise Italian ryegrass and cereals. Optimum productivity of crops grown in sequence depends on the time of sowing, the efficiency of light capture, and the suitability of selected crops with respect to their temperature adaptation. Maize is more suited to warmer climatic zones in New Zealand (Wilson et al. 1994). However, earlier modelling studies (Brown et al. 2007) have shown that yield potential in Canterbury is comparable to high producing C3 crops (Wilson et al. 2004) although the relative difference between C3 and C4 species productivity is strongly dependent on sowing dates of respective crops types (Brown et al. 2007).

This study determines the practical upper yield limits for forage crop sequences and examines the value of radiation and temperature responses to design sequences with maximum yield potential. We used crop sequences that are typical on dairy platforms or support land to supply year-round supplementary feed.

Methods

Trial design

Twelve cropping sequences (Fig. 1), comprising successive summer and winter crops, were grown over a 2-year period from 6 Oct 2007 until 5 Oct 2009. The trial was located at Lincoln, New Zealand (Lat. 43?64’S; Long. 172?45’E), on a Paparua sandy loam. The design was a split-split plot with main plots arranged in a latinised block design. Rot. 1 main plots were 46 m x 20 m with four replications. Sub plots were 6 treatments in Rot. 2 in the autumn and winter of year 1. These were split again generating 12 sequences in Rot 3 and 4 with plots 46 m x 10 m. There was balanced replication within each of paired 300 m x 50 columns, with a total of 24 plots (Rot. 1 and 2) and 48 plots (Rot. 3 and 4). Crops were managed so that water and nutrient supply did not limit yield (de Ruiter et al. 2009). All crops were sown into cultivated soils with 15 cm row spacing, except maize at 76 cm.

Biomass and cover development

Yields of summer cereals and brassicas were assessed using 0.5 m^2 quadrats, and by taking 4 m x 2 row plots of maize. Biomass of all winter crops was determined on 0.2 m^2 quadrats except for final harvests (0.5 m^2). Subsamples were dried at 90?C for 2 days for DM correction. Solar radiation interception was determined using digital photographs and the Quant software package. PAR was assumed to be 0.5 of total incident radiation. Potential productivity was determined by adding actual yield to calculations of yield loss for transition periods (days lost between harvest of a crop and sowing of the next). Potential productivity of ‘lost days’ during the season shoulders was calculated assuming full cover and the mean observed sequence RUE from 5 Oct. until sowing of the first crops in 2007. Thereafter, the mean RUE of the respective winter crops was used to calculate productivity losses resulting from delayed autumn or spring establishment. Daily air and soil temperatures (LiCor 107 probes) and total incident radiation (LiCor 200 pyranometer) were recorded on site. Thermal time (?C.d) was determined from hourly mean temperatures.

Results

Biomass

The maize-wheat-maize-triticale sequence (Seq. 1) gave the greatest accumulated crop yield of 60.1 t/ha for the 2-year period (Table 1). Sequence yields depended on whether crops included maize (Seq. 1–4), kale (Seq. 5–8) or barley (Seq. 9–12) as the summer crop. Average accumulated biomass for the respective groups were 58.5, 52.4 and 47.9 t/ha. Highest annual yield of 31.5 t/ha (for any consecutive crop) was from maize followed by triticale + faba beans (Seq. 3–4). Annual yields tended to be higher in the first year than in the second. All treatments yielded below their potential because of transition time between harvest of one crop and sowing of the next crop. Seq. 5 and 7 had the highest turnaround time (94 days), caused by frosting (on 5 Nov 2008) of an early-sown maize crop established under plastic. This was resown in barley. Seq. 10 had 82 missed production days. This was partially caused by an extra transition with a crop of rape followed by oats in Rot. 2. There was a delay in sowing of kale (Rot. 3; Seq 10 & 12) in spring as kestrel kale was oversown into a failed crop of cv ‘Gruner’ kale. Seq. 9–12 were ‘cut and carry’ crops except for barley (Seq.1) and barley in Rot. 3 (Seq. 9 & 11). The shortest transition (over 2 years) was 36 days for Seq 1.

Table 1. Yield responses to temperature and radiation for respective sequences over 2 years. Growth responses were calculated from emergence, except when calculating temperature response B.

Treatment [a]	Actual yield	Average RUE [b]	Proportion of total radiation intercepted [c]	Temperature response A [b] B [d]	Yield loss during crop transitions [d]	Potential yield [d]
	(t/ha)	(g/MJ, r^2)	%	(t/ha/100?C.d)	(t/ha)	(t/ha)

1. MwMt	60.1	2.47, (0.993)	86.7	0.810	0.702	6.3	66.5
2. MwKt	58.2	2.29, (0.985)	85.8	0.853	0.685	12.1	70.2
3. MtfbMi	58.6	2.40, (0.993)	89.7	0.792	0.684	5.2	63.8
4. MtfbKi	57.3	2.18, (0.964)	87.3	0.724	0.668	11.0	68.3
5. Kw(M)Bt	51.5	1.82, (0.991)	79.1	0.746	0.601	12.6	64.2
6. KwKt	53.6	1.74, (0.987)	89.1	0.727	0.626	6.7	60.3
7. Ktfb(M)Bi	51.9	1.88, (0.996)	78.9	0.765	0.605	14.0	65.9
8. KtfbKi	52.5	1.78, (0.987)	89.3	0.673	0.612	7.2	59.7
9. Br-oBo+i	48.6	1.83, (0.999)	85.0	0.686	0.567	7.2	55.9
10. Br-oKo+i	46.8	1.75, (0.987)	81.2	0.677	0.546	8.3	55.0
11. Bo+iBr-o	49.0	1.94, (0.992)	85.6	0.663	0.572	7.0	56.1
12. Bo+iKr	47.0	1.86, (0.982)	81.7	0.651	0.548	10.1	57.0

[a] Summer crops are indicated as upper case letters and winter crops are in lower case. M = maize, K = kale, B = barley, tfb = triticale+faba beans, w = wheat, t = triticale, r-o = rape then oats, o+i = oats + Italian ryegrass, i = Italian ryegrass, r = rape.

[b] Calculated using actual growing days (days in crop) from emergence to maturity for respective crops over entire sequence. Mean RUE (g/MJ PAR) for respective crops were: maize 2.74; late ‘Gruner’ kale 2.10; early ‘Gruner’ kale 1.56; cv ‘Kestrel’ kale 1.84; barley 2.38; wheat 1.63; triticale+faba beans 1.82; rape – oats 1.76 – 0.95; oats + Italian 2.80 (1.22 Italian regrowth); triticale 2.02; and Italian ryegrass 1.36.

[c] assuming full cover on transition days except day of sowing (0% cover).
[d] Calculated using 2-year growth duration and including missed production days.

Responses to thermal time (TT) and radiation use efficiency (RUE)

A linear model for yield response to TT fitted well for most crops in treatments 1–12 (Table 1), (r^2 >0.88) once the crop canopy had closed. The relative order for growth efficiency in response to TT was consistent whether calculated on productivity during the crop duration (from emergence to harvest) or when calculated according to the full 2-year duration of the sequences (Table 1). Highest thermal time efficiency for biomass production was 0.85 and 0.81 t/ha/100?C.d for Seq. 2 and 1 respectively, using data for crop emergence to maturity, compared with 0.69 and 0.70 t/ha/100?C.d for the respective sequences. Lowest efficiency was for combined Seq. 11 and 12 at 0.66 and 0.56 t/ha/100?C.d for the respective calculations. Of the summer crops in year 1, barley grew at a faster rate (1.63 t/ha/100?C.d) than kale (1.3 t/ha/100?C.d) or maize (1.6 t/ha/100?C.d; base 0?C) but the growth duration was shorter. The second year growth rate of maize was lower (1.2 t/ha/100?C.d) than in the previous year. Production efficiency in the winter period was less than 0.7 t/ha/100?C.d for all crops except triticale after maize or kale (Seq. 1 and 2), (Table 1).

Mean RUE values for complete crop sequences were composed of summer and winter crops that differed in their RUE, depending on position within the sequence (Table 1). Of the summer crops, maize had the highest mean RUE at 2.7 g/MJ PAR (max 2.9 g/MJ in year 1). There was a slight reduction in RUE in second year maize crops, possibly from changes in soil physical properties. In the first year, barley and kale had RUEs of 2.4 and 2.1 g/MJ PAR respectively. In the second year, kale was sown early to raise the production potential, but this did not occur (Seq. 6 & 8). RUEs declined to 1.6 g/MJ PAR, confirming observations by Sinclair & Muchow (1999) of reduced efficiency when crops are stressed or performing below potential.

For winter crops, the efficiency of light capture was much reduced and differed whether calculated using the initial growth or the regrowth following cutting. Mean RUEs for triticale and Italian ryegrass monocultures were 2.0 and 1.4 g/MJ PAR. Rape followed by oats averaged 1.2 (rape) and 0.8 g/MJ PAR (oats) alone. Oats sown in late summer and harvested in autumn performed well and had a high RUE (2.8 g/MJ PAR), but regrowth of the Italian ryegrass was lower at 1.2 g/MJ PAR. Other winter cereal crops of wheat, triticale + faba beans, and triticale had mean RUEs of 1.6, 1.8, and 2.0 g/MJ PAR, respectively.

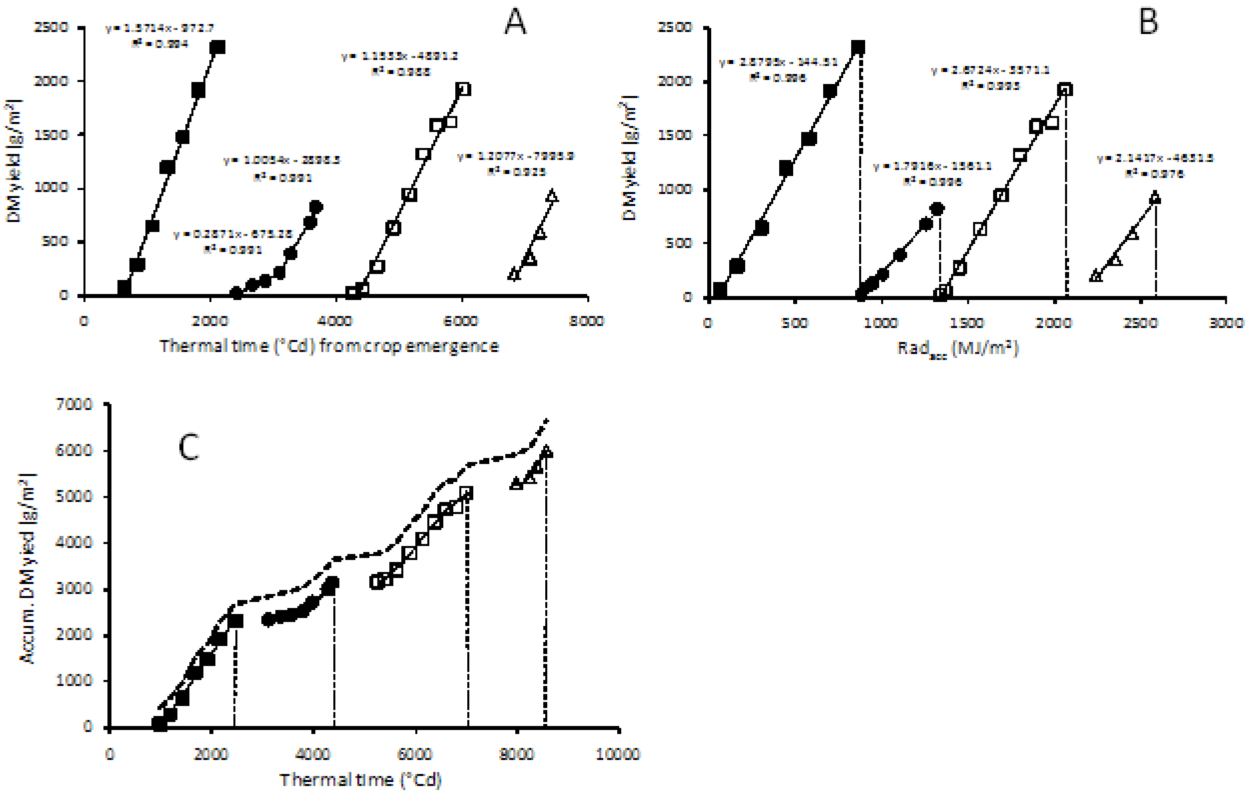

Figure 1. Productivity of best crop sequence (Trt 1) comprising maize (■) –wheat (●) – maize (□) – triticale (Δ); (A) relationship with accumulated thermal time (base 0?C) from emergence of each crop, (B) accumulated PAR intercepted (B) and (C) difference between potential and actual yield achieved in the trial (thermal time from day 1), Dotted line in (C) indicates the potential yield assuming full canopy radiation interception during transitions between crops, Vertical lines indicate forage harvests.

Discussion

Maximising yield potential of cropping sequences depends on including crops with high rates of RUE. Yield responses driven by temperature have some value if common base temperatures are used and if models for temperature-driven yield can be used across species and to compare yield responses at different latitudes. A common base temperature of 0?C was used for all crops. RUE offered a more statistically and biologically meaningful approach for examining yield differences between sequences. Moreover, we were able to use RUE to account for radiation-driven unrealised potential yield caused by lost production days between crops. The highest individual crop RUE (2.9 g/MJ PAR) was for maize in year 1. A review by Sinclair & Muchow (1999) showed that RUE was invariably higher for C4 crops than for C3. The best opportunity for achieving non-limited yield potential was in year 1, and the difference between C4 and C3 RUE was relatively small. Indeed, the yield of maize and kale was similar for much of the crop duration. Maize canopy closure was slower than other crops, but had the highest RUE. Maize yield was slightly higher than kale because the canopy closed earlier and intercepted more light. The barley crop in the first year averaged 2.4 g/MJ PAR but the yield potential was lower because of its short duration.

For complete sequences over 2 calendar years, the proportion of light used for biomass production was 78.9– 89.7%. This accounted for transition time losses and proportional losses during canopy development leading to full canopy closure. Therefore, there was potential for between 10 and 21% more yield possible than that observed in the trial (Fig. 1C). Calculated yield losses during crop transition were

7.0–14.0 t/ha (Table 1). The largest yield losses occurred in Seq. 5 and 7 with failure of an early sown maize crop. Total potential yield (actual + crop transition loss) was a maximum of 70.2 t/ha. The highest yield was reached with maize as the first summer crop. Lesser yields were reached with kale and barley as first crops in the sequence.

Calculations of average sequence RUE (for days in crop) were good predictors of total sequence productivity (r^2=0.72) while not accounting for transition time on total yield. There were small differences in the rate of canopy closure between crops and differences in the RUE for individual crops. Brown et al. (2007) concluded that 32 t/ha/annum could be grown under perfect conditions. Our trial showed that, with delayed canopy closure and the reality of breaks between crops, yields of 60 t/ha were achieved over 2 years but, with optimum management, could reach 70 t/ha. Highest productivity was from crops with high RUE, which have the highest growth rates during periods of highest radiation if the canopy is closed Kale, like maize, had an extended growth duration. Yield in Seq. 9–12, with two short duration summer crops (barley followed by rape) was compromised because of the extra transitions.

Modelling crop production potential has shown the effects of latitude, temperature responses and best sowing dates for C3 and C4 species (Brown et al. 2007). Our attempts to achieve an industry target of 45 t/ha/annum at Lincoln were short by 10 t/ha/annum, and it is unlikely that annual yield could be improved further by selecting other species or improving crop management. The future challenge is how to integrate the crops effectively into the whole farm feeding systems and show profit from increased milk production.

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