

Aiming for 45 t/ha per annum: yield of supplementary feed crops grown in sequences designed for maximum productivity

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Abstract

Dairy industry strategies have demanded feeding systems with high productivity and high quality. A 45 t DM/ha annual target for feed production was addressed. Six crop sequence treatments were established in large plots (40 x 12 m) at Lincoln, Canterbury, in the first year of a 2-year experiment to determine practical upper limits for yield. Summer crops included maize, kale and whole crop barley and these were followed by combinations of winter crops (oats, Italian ryegrass, forage rape, tick beans and triticale). Crops were grown with minimal transition time to reduce potential yield losses, and with optimum nitrogen and irrigation management. Highest plot yield in the first annual crop cycle was 11.9 t DM/ha short of the 45 t DM/ha target. Best productivity was with a maize – triticale+tick bean (32.5 t DM/ha) sequence followed by maize – wheat (30.0 t DM/ha), barley – oats+Italian ryegrass (28.1 t DM/ha) and kale – triticale+tick bean (26.1 t DM/ha). Fertiliser management, crop water use in high input cropping systems are discussed together with practical issues around handling crops with large accumulated biomass.

Keywords: dairying, supplements, forage quality, nitrogen, water use

Introduction

Feed production in New Zealand's pastoral industries can be increased by sowing more productive pasture species (Lambert *et al.* 2004) and by having a higher proportion of farms in high producing supplementary feed crops. Increased dairy production has required that more feed be grown to support the growing numbers of cows, particularly in the southern regions (DairyNZ 2008).

A renewed interest in supplementary feeds such as whole crop silage (de Ruiter *et al.* 2002; Milne 2007; Platfoot & Stevens 2002) maize silage (Dalley *et al.* 2005; Densley *et al.* 2005b) and brassicas (Hogg *et al.* 2002) has been driven by the demand for higher per cow performance. Maize for silage has been considered in southern latitudes (Wilson *et al.* 1994) with the main option being short maturing hybrids to reduce the risk of crop failure. Summer fed turnips (Eerens & Lane 2004) and grazing-type brassicas such as leafy turnips

and rape are less risky options over a range of latitudes, but must be fed 'in situ'. Winter cereals and annual ryegrass are also important options in cropping systems because of their flexibility of use as grazed feed, cut and carry feed or silage (Densley *et al.* 2006; Hogg *et al.* 2002). These crops can provide high energy supplement for extending autumn lactation (Waghorn 2007) or be utilised for winter or spring feeding.

To achieve high productivity, crops selected for forage should match the intended environment. Many studies have shown that productivity is related to radiation use efficiency. Therefore, high yield is expected from crops with their growth duration occurring largely during periods of high radiation. Crops such as kale with extended growth durations have also given high yields, but their average daily productivity may be lower than that of short-term crops like spring cereals. Crop potential modelling has shown that productivity depended on latitude and therefore the temperature pattern (Brown *et al.* 2007a). Also, the relative contributions of C₄ and C₃ species changed with choice of sowing time and location (Brown *et al.* 2007a). Appropriate sowing dates and cultivars or hybrids (Densley *et al.* 2005a) will be important for achieving close to potential yield. Techniques that reduce the transition time between crops will also ensure that annual productivity will be close to optimum (Brown *et al.* 2007a).

This paper describes cropping sequences suitable for implementation on dairy platforms or runoffs as the model system for maximising crop yield. The experiment tested the practical productivity limits using cropping sequences that would fit within current farming practices, have minimum impacts on the environment and provide a 2-year break between pasture to pasture in renewal programmes.

Methods

Summer and winter crops were grown on a Paparua silt loam soil (sand at 30-50 cm) in a cropping sequence experiment at Lincoln, New Zealand (Lat. 43°64'S; Long. 172°45'E). The experiment was initiated in October 2007 with 12 treatments over 2 years. The first cycle of crops (Sequence 1) included maize, kale and barley in the first summer. These were split to give 6

Table 1 Sowing, emergence and maturity harvest dates, and accumulated yield for crops in Sequences 1 and 2.

Sequence 1	'Cropping' treatments				'Silage – grazing' treatments	
	Maize ('P39G12')		Kale (cv 'Gruner')		Barley (cv 'Salute')	
Sowing	23 Oct 07		25 Oct 07		23 Oct 07	
Emergence	4 Nov 07		1 Nov 07		30 Oct 07	
Maturity	25 Mar 08		30 Mar 08		29 Jan 08	

Sequence 2	Treatment	1	2	3	4	5	6
		Wheat (cv 'Morph')	Triticale (cv 'Crackerjack') and tick beans (NZ variety)	Wheat (cv 'Morph')	Triticale (cv 'Crackerjack') and tick beans (NZ variety)	Rape ('Goliath') then Oats (cv Milton)	Oats (cv 'Milton') and Italian ryegrass ('Feast II') mix
Sowing		28 Mar 08	28 Mar 08	1 Apr 08	1 Apr 08	1 Feb 08 (R) 19 May 08 (O)	1 Feb 08 15 May 08 (It) ^a
Emergence		8 Apr 08	5 Apr 08	12 Apr 08	12 Apr 08	11 Feb 08 (R) 6 Jun 08 (O)	8 Feb 08
Maturity		13 Oct 08	13 Oct 08	12 Sept 08	16 Sep 08	16 May 08 (R) 13 Oct 08 (O)	15 Apr 08 (O) 13 Oct 08 (It)
Accumulated Yield (t DM/ha)		30.0	32.5	24.4	26.1	24.0	28.1
Standard Error (t DM/ha) ^b		2.88	2.61	4.32	4.42	2.58	2.99

^a Undersown with Italian ryegrass; ^b pooled standard error of final yield of respective sequences; (R)=Rape, (O)=oats.

Table 2 Crop management inputs for summer crops (Sequence 1).

Management	Maize ('P39G12')	Kale (cv 'Gruner')	Barley (cv 'Salute')
Fertiliser at sowing	300 kg/ha Nitrophoska + 50 kg/ha N (urea)	300 kg/ha DAP + 15 kg/ha Boronate	150 kg/ha Cropmaster 15
Fertiliser during growth	125 kg N/ha (urea)	250 kg N/ha (urea)	2 x 50 kg N/ha (urea)
Total N: P: K: S (kg/ha)	211: 30 :30: 1.2	282: 44: 0: 38	123: 15: 15: 12
Herbicide	Lasso (7 L/ha a.i. Alaclor) + Bladex (1.1 kg/ha ai cyanazine)	Treflan (1.7 L/ha) (pre sow)	
Insecticide	Treated seed Lorsban (1L/ha)	Superstrike seed trt Diazinon (1 L/ha)	Vitaflow and Poncho seed treatment 150 ml/ha Pirimor 40 ml/ha Karate
Fungicide	None	None	Vitaflow seed treatment. 400 ml/ha Proline 300 ml/ha Opus 400 ml/ha Amistar
Growth regulator	None	None	200 ml/ha Moddus

treatments in the second sequence (Sequence 2) in the autumn and winter of Year 1 (Table 1). Crop selections for the respective sequences were designed to maximise dry matter (DM) production. Treatments 1-4 had maize or kale as the main summer crop. Treatments 5 and 6

included grazed crops (rape, oats, multi-graze triticale) and whole crop silage barley. In May 2009, treatments were split to form 12 treatments. However, only data from the first 12 months (Sequences 1 and 2) are presented. Maturity dates in treatments 3 and 4 were 1

Table 3 Management inputs for autumn and winter crops (Sequence 2).

Management	Wheat (cv 'Morph')	Triticale (cv 'Crackerjack') and tick beans (NZ variety)	Rape ('Goliath') then oats (cv 'Milton')	Oats (cv 'Milton') and Italian ryegrass (cv 'Feast II') mix
Fertiliser at sowing	200 kg/ha CropZeal20N	200 kg/ha CropZeal20N	Rape: 200 kg/ha CropZeal20N + 15 kg/ha Boronate	Oats + Italian: 200 kg/ha CropZeal20N
Fertiliser during growth	None	None	Oats: 200 kg/ha Cropmas- ter 15 100 kg N/ha (urea) 50 kg N/ha (urea)	2 x 100 kg N/ha (urea)
Total N: P: K: S (kg/ha)	39: 20: 0: 24	39: 20: 0: 24	219: 40: 20: 39	129: 20: 0: 24
Herbicide	None	None	None	None
Insecticide	20 ml/ha Karate	20 ml/ha Karate 20 ml/ha Karate	1 L/ha Lorsban	4 kg/ha Metarex
Fungicide	2 L/ha Protec (Car- bendazim) 200 ml/ha Opus 500 ml Opus	2 L/ha Protec (Car- bendazim) 200 ml/ha Opus 500 ml/ha Amistar		

Table 4 Mean monthly (2007/08 season) and long term (34 yr) climate summary for Lincoln.

Month	2007–08						Long term (1975–2008) mean					
	Rainfall (mm/ month)	Temperature (°C)			Mean Daily Radiation (MJ/m ²)	Penman ET (mm)	Rainfall (mm/ month)	Temperature (°C)			Mean Daily Radiation (MJ/m ²)	Penman ET (mm)
		Max	Min	Mean				Max	Min	Mean		
October	79.2	16.9	5.0	11.0	18.4	4.0	54.9	16.7	6.0	11.3	16.4	3.4
November	41.5	18.3	7.6	12.6	23.5	4.4	55.7	18.4	8.0	13.1	20.1	4.1
December	58.8	20.5	11.0	15.3	22.9	4.6	61.3	21.3	10.2	15.7	21.7	4.6
January	19.2	22.7	12.0	17.1	23.3	5.1	50.3	22.6	11.4	17	21.6	5.1
February	105.4	21.1	12.4	16.1	18.6	4.0	51.3	21.7	11	16.3	18.4	4.0
March	23.6	20.4	10.0	14.9	14.4	3.0	58.9	20.1	9.9	15.0	13.6	3.1
April	35.7	17.5	6.7	12.1	9.0	1.9	51.8	17.5	6.7	12.2	9.6	2.1
May	53.9	12.8	2.5	7.4	5.9	1.0	50.4	13.8	3.7	8.7	5.7	1.4
June	88.9	12.1	1.6	7.0	4.2	1.0	63.0	11.2	1.5	6.3	4.2	1.1
July	145.0	10.7	3.0	6.7	4.3	0.9	73.7	10.7	1.4	6.1	4.7	1.2
August	94.2	10.9	2.1	6.3	7.3	1.3	68.1	12.2	2.9	7.6	7.1	1.6
September	39.1	15.8	5.2	10.4	11.4	2.5	40.1	14.2	4.3	9.2	11.3	2.3

month earlier than treatments 1 and 2 to accommodate early sowing in following sequences (Table 1).

Design

In Sequences 1 and 2, plots were 46 x 20 m with 4 replicates. Plots in Sequence 3 and 4 were split into 50 x 12.5 m plots and randomly assigned to main plots. The design was a split-plot with main plots arranged

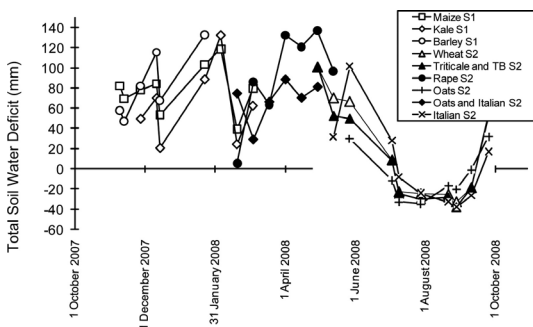
in a latinised block design. Main plot treatments were arranged with complete replication for all crop sequences. There was also balanced replication within each paired 300 x 50 m column containing 12 plots (Sequences 1 and 2). Column dimensions were designed to accommodate a lateral irrigator with a 50 m boom. Plots were separated by 8 m perennial ryegrass buffers.

The experimental area was previously in lucerne

Table 5 Soil mineral nitrogen and available mineralisable nitrogen (AMN, ARL Laboratories) measured pre-season^a and level remaining in soil following the respective crops^b. End of oat cover crop^c treatment 11 and 12 (18 Apr 08) followed by ^dItalian ryegrass at end of Sequence 2.

Depth (cm)	Sequence 1 ^b			Sequence 2 ^b							
	1 Sep 07 ^a	29 Jan 08	26 Mar 08	15 Sep 08		7 Oct 08					
	Barley	Kale	Maize	Triticale + tick beans	Wheat	Triticale + tick beans	Wheat	Rape then oats	Oats then Italian		
Mineral nitrogen (kg/ha)											
0-20	22.1	18.2	21.4	76.9	30.0	41.2	36.9	29.7	24.1	10.5	
20-40	14.4	13.0	9.0	48.8	8.9	17.2	17.5	11.7	31.5	9.5	
40-60	11.0	12.5	5.8	28.8	4.2	7.3	16.4	5.7	38.7	7.8	
60-80	10.0										
60-90		18.6	10.6	34.6	7.4	10.2	16.1	9.6	63.6	33.0	
80-100	6.9										
90-120		14.0	12.0	50.6	10.8	20.8	27.2	20.5	52.2	59.4	
120-150		11.4	13.3	30.8	16.1	37.1	39.6	31.9	44.7	51.3	
Available mineralisable nitrogen (kg/ha)											
0-20		40.0	75.3	58.5	72	50	91	61	91	59.3 ^c	55 ^d
20-40		44.6	23.8	26.8	25	27	26	29	24	26.8 ^c	20 ^d
40-60		-	-	-	5	10	8	11	7	-	9
60-90		-	-	-	2	5	3	3	2	-	5
90-120		-	-	-	3	4	1	1	3	-	3
120-150		-	-	-	2	1	1	1	1	-	2

Figure 1 Measured soil water deficits during the summer and winter under Sequences 1 (S1) and 2 (S2). Drained upper limited (deficit = 0) was assumed at soil moisture 30% (v/v).



(*Medicago sativa*) and was sprayed out with 3L/ha G-Force MAX (a.i. 540 g/L Glyphosate) plus 30 g/ha Granstar (a.i., tribenuron methyl) on 31 July 2007. The area was ploughed on 7 September then rolled and lime applied at 2.5 t DM/ha. Sequence 1 crops of barley (*Hordeum vulgare* cv 'Salute'), kale (*Brassica oleracea* cv 'Gruner') and maize (*Zea mays* hybrid 'P39G12') were sown on 23 October, 25 October and

23 October (Table 1), respectively, at 150 kg/ha, 4 kg/ha and 116,000 seeds/ha. Sowing dates of following crops in the sequence are given in Table 1. Sequence 2 crops were sown into cultivated seedbeds. In treatment 5, an additional crop of oats (cv 'Milton') was direct-drilled into the rape stubble following an early winter harvest. Management treatments for both summer and following winter crops are given in Tables 2 and 3.

Soil moisture

A single neutron probe access tube was installed in all main plots shortly after crop emergence and soil moisture was monitored at 20 cm depths down to 1.50 m. Mean profile volumetric soil deficits were calculated for each crop and these were used to adjust irrigation application volume. Irrigation was applied weekly during periods of maximum evapotranspiration.

Biomass and partitioning

Plot yields were measured fortnightly by taking 0.5 m² quadrats for field fresh weight of barley and kale, and by 4 x 2 m rows of maize. Subsamples were dried at 90°C for 2 days for DM correction. Subsamples were also taken for leaf area determination (two maize plants, five

kale and 20 barley tillers) and for partitioning of plant fractions (leaf, stem, or ear (maize and barley)). Leaf area was measured using a model LI-3100 area meter.

At the maturity harvest, additional 'large' quadrat samples were taken to confirm yield as quadrat dimensions were increased to 4 m² (maize), 1 m² (barley) and 3 m² (kale). Plant N was determined on a TruSpec CN Determinator using EDTA standards.

Soil analysis

A pre-season MAF Q-test (1 July 2007) for the 0–15 cm depth was pH 5.7, Ca 6, Olsen P 23, K 15, S(SO₄) 12, Mg 10, Na 6. A subsequent soil test on 12 September (after cultivation) showed pH 5.9, Ca 8, Olsen P 14, K 9, S(SO₄) 5, Mg 7, Na 7.

Soil chemical components were determined before sowing (before fertiliser application) for each plot by sampling to 0–20, 20–40, 40–60, 60–90, 90–120, and 120–150 cm depths. Duplicate cores were bulked and analysed for mineral N (2M KCl extraction and analysis using a Foss FIAstar 5000 Analyser), AMN available mineral N (ARL Lab.), and minerals (MAF Quick Test, ARL Lab).

Soil solution N was recovered from depths of 0.60 and 1.50 m by withdrawing aqueous samples from 3.5 cm diameter PVC tubes equipped with ceramic porous tips. Soil solution was extracted under vacuum if a drainage event was predicted at 60 cm depth using a leaching model and if rain or irrigation exceeded 15 mm. Nitrate and ammonium was determined on aqueous samples by flow injection analysis as above.

Daily crop water use was calculated for the summer crops from the change in soil moisture driven by Penman evaporation. Changes in soil moisture were adjusted for rain, irrigation and calculated leaching losses. A sequential crop modelling system (LUCI Framework Model) (Zyskowski *et al.* 2007) was used to predict potential drainage and mineral losses following summer crops of barley, kale and maize. Comparisons were also made between model predictions for soil mineral N loss and observed losses to ground water as measured by soil solution samplers during the summer and winter.

Climate data

Daily air and soil temperatures (LiCor 107 probes) and total incident radiation (LiCor 200 sensor) were recorded on site with Campbell loggers located adjacent to main crops of maize, kale and barley. Rainfall and irrigation were recorded with a 0.2 mm tipping bucket gauge located at the site of the experiment (Table 4).

Results

Climate

In the 2007–08 season, rainfall was above average in October and February, but January and March were especially dry (Table 4). June, July and August were considerably wetter than average. This was important for drainage and N leaching observations as discussed later. Mean monthly temperatures were within 0.4°C of long-term averages. Temperature ranges were surprisingly close to averages for the respective months, as was the Penman evapotranspiration (mm) (Table 4). Radiation was higher than average for the months October to January but close to average for the remainder of the year.

Soil tests

Readily available (nitrate and ammonium) levels were comparatively low (64 kg/ha calculated to 1 m depth) at the start of the experiment following a long-term lucerne crop. During the experiment there were varying levels of residual nitrogen present in the soil at crop harvest (Table 5). Some of this nitrogen was derived from fertiliser not used for plant uptake. The summer maize crop and autumn oats had particularly high residual mineral N remaining (0–1.50 m depth) at harvest.

Water use and soil moisture

Crop water use by the respective crops of barley, kale and maize was 398, 650 and 659 mm. Total irrigation was 224, 366 and 366 mm, with calculated total leaching losses of 0, 122 and 52 mm, respectively.

Measured soil water (Fig. 1) showed summer crops were rarely under any level of stress assuming the soil water holding capacity ($0.08 < \theta < 0.30$) to 1.50 m depth was 360 mm. The soil was sandy at lower depths and therefore the volumetric water content (θ) at wilting point was likely to be higher than the assumed value of 0.08 (v/v). The autumn rape crop showed signs of leaf wilting when evaporative demand was high one day in early March when maximum air temperature exceeded 30°C. Measured water content during winter was typically higher than the assumed drained upper limit of $\theta = 0.30$ (Fig. 1).

Yield

Summer crops

Maize emerged on 4 November 2007 and established a mean population of 108,333 plants per m². High populations of kale (78.5 plants/m²) and barley (324 plants/m²) were also established. All crops were set up to produce maximum yield with optimum rates of N applied and irrigation water supplied. Irrigation was applied to maintain soil water deficits within the non-

Figure 2 Cumulative biomass (t DM/ha) of crops in respective sequences beginning with maize (A), kale (B) and barley (C).

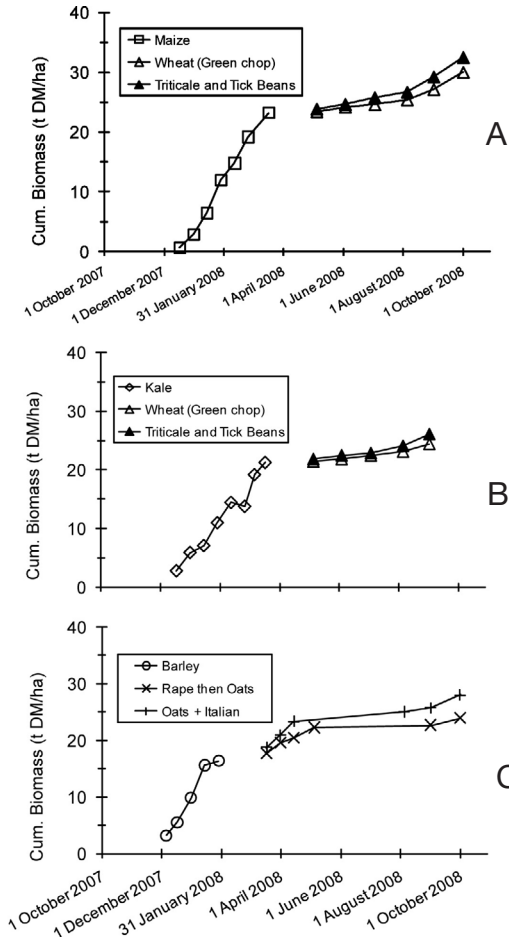
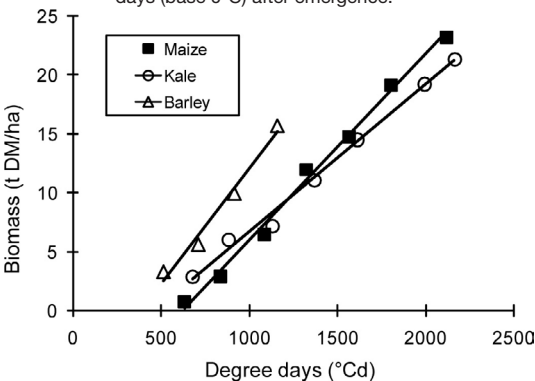


Figure 3 Biomass (t DM/ha) summer crops. Regressions: maize, $y = 0.157x - 7.378$ ($r^2 = 0.98$); kale, $y = 0.0125x - 5.776$ ($r^2 = 0.99$); and barley, $y = 0.0194x - 9.727$ ($r^2 = 0.99$) where x is thermal time in degree days (base 0°C) after emergence.



restricting range and ideally in the range 0–80 mm. There were several occasions when deficits approached 140 mm (Fig. 1).

The highest accumulated growth rate for summer crops was achieved for barley at 182.7 kg DM/ha/day, but the crop duration was much shorter than for maize or kale (Table 6). Barley was cut for whole crop silage with a yield of 16.4 t DM/ha and DM content of 35.6%. The crop was harvested earlier than anticipated but it was beginning to lodge, so a small yield penalty was incurred with incomplete grain filling. Harvestable biomass for maize (C₄) was higher than for kale (C₃) with mean growth rates from emergence to maturity of 158 and 172 kg DM/ha/day, respectively. Both maize and kale developed a similar maximum leaf area (Table 6).

Barley was harvested at a time of the year when incoming radiation levels were high and consequently there was a potential yield loss resulting from incomplete cover and inefficient use of incident radiation while the following crop was established. However, early barley harvest created an opportunity to establish crops that could take full advantage of the warm temperatures in March and April and before declining temperatures reduced productivity during late autumn.

Summer maize and kale crops harvested in autumn, accumulated more yield than the early harvested barley, despite lower mean growth rates. Longer crop durations compensated for the lower mean growth rates.

Winter crops

Crops sown after barley were ‘Oats + Italian ryegrass mix’ and sequential crops of ‘Rape followed by Oats’. The former produced high quality forage comprising 6.7 t DM/ha oats and 0.28 t DM/ha ryegrass by 15 April. Mean growth rates (106 kg DM/ha/day) were comparatively high in autumn. The oats were windrowed and wilted before baling for silage. Side-raking caused some damage to developing Italian ryegrass seedlings and the crop was oversown to establish an even population. Ryegrass regrowth yielded 4.1 t DM/ha by 17 October. The treatment of rape (following barley) also yielded well (5.9 t DM/ha) at a 16 May harvest. This was resown by direct-drilling on 19 May into oats for a further yield of 1.7 t DM/ha by 13 October. Winter growth rates of the Italian ryegrass/oats mix were slow at 28.1 and 14.1 kg DM/ha/day over lengthy crop duration (167 and 117 days).

The growth of ‘Triticale and tick beans’ and ‘Wheat’, after late harvest of kale and maize, was compromised by declining soil temperatures in April and May. Yield of ‘Triticale + tick beans’ was higher than for wheat when following maize or kale. The contribution of tick beans to the mix was approximately half the total yield until canopy closure after which the cereal was a strong

Table 6 Plant population, yield, mean growth rate over crop duration and maximum leaf area index for crops in Sequences 1 and 2.

	Mean population (plants per m ²)	Biomass (t DM/ha)	Growth rate (kg DM/ha/day)	Growth duration (days)	Max. leaf area index
Sequence 1					
Maize	11.3 (0.67)	23.2 (0.57)	172.0	146	5.7 (0.85)
Kale	52.1 (12.1)	21.3 (2.96)	157.8	135	6.2 (0.85)
Barley	332.8 (97.3)	16.4 (1.02)	182.7	90	4.4 (0.39)
Sequence 2					
<i>Following maize</i>					
Wheat	232.0 (49)	6.8 (1.02)	38.7	176	6.5 (1.1)
Triticale	252.0 (27.5)	9.0 (0.75)	50.9	176	5.75 (0.62)
+ tick beans	83.8 (19.3)	0.34 (0.15)	1.9 (11.1 ^a)	176	0.75 (0.12)
<i>Following kale</i>					
Wheat	213.0 (27.5)	3.1 (0.49)	21.9	142	3.62 (0.54)
Triticale	281.0 (36.4)	4.4 (0.67)	31.2	144	5.02 (1.39)
+ tick beans	77.5 (25.0)	0.34 (0.08)	2.4 (8.9 ^a)	144	0.65 (0.13)
<i>Following barley</i>					
Rape (R)	128.0 (36)	5.9 (0.95)	69.9	84	4.93 (0.65)
then Oats (O)	292.1 (42.1)	1.7 (0.18)	14.1	117	2.32 (0.18)
Total (R+O)	-	<u>7.5 (-)</u>	<u>31.2</u>	<u>243</u>	-
<i>Following barley</i>					
Oats (O)	-	6.7 (0.57)	105.8	66	4.28 (0.92)
+ Italian RG	-	0.28 (0.07)	4.4	66	0.42 (0.18)
Total	-	6.9 (-)	10.2	66	-
Italian RG	-	4.7 (0.99)	28.1	167	-
Total (O+It)	-	<u>11.6 (-)</u>	<u>20.1</u>	<u>233</u>	-

^a Maximum growth rate during early establishment. Other values in brackets are standard errors.

competitor. The final tick bean yield in the mix was 5–10% of the total yield.

Accumulated yield

The best combination ('Maize' – 'Triticale + tick beans') produced 32.5 t DM/ha, which was 72.2% of the target of 45.0 t DM/ha (Fig. 2). The cropping treatments (1–4) were more productive than the 'silage-grazing' options (Treatments 5 and 6) despite having the crop (barley) with the highest mean growth rate and three crops rather than two in the sequence. The lower yield in this combination supports the hypothesis that transitions between crops e.g. 'Barley – Oats' and 'Barley–Rape' during periods of high radiation had a marked effect on productivity. Accumulated yields at the completion of Sequence 3 crops (second summer) are shown in Fig. 2.

Discussion

This study shows that sequences of crops can produce annual dry matter yields approaching 30 t DM/ha in the South Island. Under ideal summer conditions in Canterbury, maize can be grown reliably with yields in excess of 20 t DM/ha. However, maize harvest in late March or early April compromises following crops, such as cereals, which require good early autumn growth to achieve acceptable growth rates into the winter.

High autumn kale yields created difficulties for the utilisation or conservation of the biomass produced. Standing kale was wind-rowed and allowed to wilt for 7 days with a slight rise in DM% (11.9 to 13.5%). During wilting, the stems became more flexible and sufficiently less brittle for successful pick-up and chopping using a pasture forage harvester. The material was fine-chopped

and fed as fresh crop to stock. Alternate methods for handling high biomass kale by either direct-chopping and feeding in a 'cut and carry' operation or mixing the crops with mature high DM crops, such as maize or whole crop cereal are required to balance the DM% of a mixed kale silage (Moorby *et al.* 2003). Barley was wind-rowed and baled for whole crop silage at a 31% DM content. This was lower than ideal for silage but it had to be taken early because the crop was beginning to lodge.

Differences in growth of summer crops were observed when plotting accumulated biomass against thermal time with a base temperature of 0°C (Fig. 3). The C₃ crops (barley and kale) had a shorter lag phase than C₄ (maize) leading to linear growth. For barley and kale, cover had reached 95% before the first biomass measurement and it was 47% at the first maize biomass harvest. Mean production efficiency was highest for barley (19.4 kg DM/ha/°Cday), intermediate for maize (15.7 kg DM/ha/°Cday) and lowest for kale (12.5 kg DM/ha/°Cday). Early kale growth was more responsive to thermal time than maize but the growth efficiency of maize was higher than kale from mid-way through development to maturity. Maize probably has a higher radiation use efficiency later in development in addition to higher growth rate response to temperature. However, maize was less efficient when low temperatures limited growth and canopy development during early growth.

The advantages of using barley in a high producing sequence lies in its ability to achieve rapid canopy closure and its high growth rate. However, its short crop duration means following crops need to be established during warmer months with peak incident radiation. The mean growth rates of barley were significantly higher than the 8.0 kg DM/ha/°Cday reported for well-managed kale (Brown *et al.* 2007b) sown on three dates in spring in Canterbury. Rates for barley were also higher than reported by de Ruiter (2001) for a range of spring-sown cereals (10.8–17.7 kg DM/ha/°Cday).

Good N management was important for achieving high yielding summer crops. However, there are real risks of excess leaf vegetative growth, making harvesting difficult and raising the potential for N to build up in the soil if fertiliser is not used or excess irrigation/rainfall move mobile N lower in the soil profile. In the first summer, there were high levels of residual N in the soil at maize harvest, but this was taken up by the following cereal. Nitrogen lost by leaching was not considered large given the high rates applied to maximise production. In winter there was evidence of movement of mineral N into the 150 cm layer and potential N loss from the rooting zone. This was more likely to occur under low producing crops

such as wheat and Italian ryegrass.

The experiment was designed to maximise the production of crops grown in sequences with the aim of achieving a target of 45 t DM/ha. The highest individual plot yield of 38 t DM/ha was achieved with sequence crops of 'Maize' followed by 'Triticale + tick beans'. However, the mean for this treatment was 32.5 t DM/ha. Alternatives comprised a C₃ 'Kale' crop grown for the same duration as a 'Maize' crop and 'Triticale + tick beans' which yielded only 2 t DM/ha less. Target yields were not met but crop durations were maximised by ensuring rapid turnaround between crops and minimising the duration when crops were not at full cover and therefore not intercepting maximum incident radiation. A similar study in Australia which targeted 40 t DM/ha/annum biomass used complementary cropping sequences of rape, Persian clover and maize (Garcia *et al.* 2008). A mean annual yield of 42.3 t DM/ha was achieved over 3 years. In the North Island, annual yields of 39.6 t DM/ha were achieved with maize and triticale crop sequences (Densley *et al.* 2006b). Sequences of maize and Italian ryegrass or oats yielded 5–8 t DM/ha less than this.

Theoretical crop production potentials in C₃/C₄ cropping sequences were shown to be equivalent to the industry target of 45 t DM/ha/annum in northern regions of New Zealand with combinations of crops grown with no transition time and with no water or nutrient stress (Brown *et al.* 2007a). These analyses were performed using validated crop simulations with the Sirius wheat model (Jamieson *et al.* 1998; Brown *et al.* 2007a) and the AmaizeN model (Li *et al.* 2007). A kale model has also been used to predict biomass production under a range of sowing dates and locations (Wilson *et al.* 2004). In practice, two and three crops/year grown close to maximum yield is difficult to achieve because of climatic variability and difficulties with the timing of key processes such as cultivation and sowing. Lost productivity due to water and nutrient stress is invariably not recovered (Jamieson *et al.* 1998).

Future studies will address the scale of yield loss caused by incomplete cover development and the potential yield attainable when there is no nutrient or water limitation. This experiment is continuing for 24 months with alternative crop selections in Year 2. Multiple-graze triticales, for example, provide additional flexibility with equally good early growth and high protein source for multiple grazing in winter as well as a silage option in late spring. These crops have a high nutritive value in the vegetative stage and suitable quality for carrying through to silage. Testing of best cropping sequences for commercial dairy operations is planned.

Conclusions

High productivity, low environmental impact, flexible feed utilisation options and high herbage quality are the basis of crop sequence design for supplementary feeding in dairy production systems in New Zealand. Maximum annual yield from Year 1 of a 2-year study was up to 72% of the target of 45 t DM/ha/yr. The best production was achieved from sequences of maize followed by a blend of triticale and tick beans. October sown kale also gave a high biomass crop and with optimum management produced its utilisable yield by the end of March. This meant alternative utilisation strategies were required for use in feeding systems.

Sowing date and cultivar selection are important for maximising yield. This was especially important for autumn crops which responded to warm soil and air temperatures. Early maturing barley for silage was useful when followed by oats or rape, producing 6.7 and 5.9 t DM/ha, respectively, for late autumn grazing. Year 1 of the experiment with six different sequences showed little loss in quality resulting from management methods aimed at maximising yield.

Environmental concerns around the excess loss of soluble N forms to ground water remains a priority especially in systems designed for maximum biomass production. Not only are there increased risks when fertiliser is applied at high rates to achieve high yield it also means there is more biomass to pass through the animal resulting in highly concentrated N returns being reapplied to the land during grazing. It is probable that cut and carry systems will have to be developed to minimise the environmental risks and systems developed to spread the effluent load.

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