Possible species for the production of biodiesel on marginal land

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Abstract

A series of field experiments was conducted in 2009-10 and 2010-11 in the North and South Islands of New Zealand to examine the potential of brown mustard (*Brassica juncea*); camelina or false flax (*Camelina sativa*); meadowfoam (*Limnanthes alba*) and field penny-cress (*Thlaspi arvense*) with oilseed rape (*Brassica napus*) as the current NZ biodiesel crop. Crops were grown at three sites in both years; Ashley Dene (dryland sheep farm, Lincoln), Oxford (wet, low fertility land in the foothills of the Southern Alps) and Taupo (central North Island light pumice soil). There were both autumn and spring sowings at all sites in 2009-10, but in 2010-11, Taupo and Oxford had spring sown trials only. In 2009-10 all species established well after sowing with the exception of field penny-cress. At Taupo and Oxford oilseed rape yielded up to 2.3 and 3.8 t seed ha^{-1} respectively, but at Ashley Dene it yielded less than 1 t seed ha^{-1}. Brown mustard and camelina performed nearly as well at some sites, producing up to 2.9 t seed ha^{-1} at Taupo, yet at Ashley Dene, camelina produced just 0.9 t seed ha^{-1}. Meadowfoam had the highest seed yield of nearly 1.6 t ha^{-1} at Ashley Dene, and, at Taupo and Oxford, it yielded up to 1.0 and 0.6 t seed ha^{-1} respectively. Seed oil contents within species were similar across all sites. Oilseed rape had the highest oil content, averaging 40% followed by brown mustard (35%) and camelina (33%). Field penny-cress and meadowfoam were lower, averaging 24% and 15% respectively. Oil yields followed a very similar trend to seed yield. Maximum oil yields of 1.5 and 1.0 t ha^{-1} were attained by oilseed rape at Oxford and Taupo respectively. Most other sites, sowings and species combinations produced less than 600 kg oil ha^{-1}. In 2010-11 the crops were much less productive than in the previous year. This was mostly due to weather events - significant late rainfall at Taupo causing disease problems and destruction of bird netting by high winds in Canterbury allowing birds to eat the seeds. As a consequence, oil yields were less than half of the previous year in those sites. The maximum oil yield was 967 kg ha^{-1} from oilseed rape sown in September at Oxford. This study has shown the adaptability of oilseed rape to marginal environments and the potential of camelina as an alternative biodiesel crop.

Additional keywords: *Brassica napus*, *Brassica juncea*, *Camelina sativa*, *Limnanthes alba*, *Thlaspi arvense*, yield, oil content, sowing date, sites

Introduction

In 2006 the New Zealand government passed legislation that required oil companies to meet a biofuels sales obligation which required that by 2012, 3.4% of total petrol and diesel sold be biofuel. This legislation has since been repealed. However there is increasing interest in biofuels worldwide as the price of petrol and diesel continues to increase (Timilsina and Shrestha, 2011). Ethanol is now widely used as a substitute for petrol.

However, over 50% of the transport fuel used in New Zealand is diesel (Ministry of Economic Development, 2011) and biofuel alternatives for biodiesel have not been widely researched (Painter, 2009). There has also been much concern, particularly in the USA and Europe, over the utilisation of high quality cropping soils to grow biofuels and the use of food crops to produce biofuels (Timilsina and Shrestha, 2011).

The objective of this project was to examine the potential of a range of oilseed species to produce biodiesel on marginal land, i.e. land with limitations to growing high yields of food crops. Five species were selected on the basis of yield, oil content, ability to grow on marginal agricultural land and not being currently grown for food. These were:

Brassica napus L. (oilseed rape [OSR]); *Brassica juncea* (L.) Czern. (brown mustard [BM]); *Camelina sativa* (L.) Crantz (camelina or false flax [CS]); *Limnanthes alba* Hartw. Ex Benth. (meadowfoam [MF]); *Thlaspi arvense* L. (pennycress or field penny-cress [PC]). These were grown at three sites representative of large tracts of marginal agricultural land in New Zealand.

Materials and Methods

In 2009-10 and 2010-11 the five species (OSR, CS, BM, MF and PC) were grown on marginal soils at three sites (Table 1). These were: Ashley Dene, a dryland sheep farm on Balmoral very stony silt loam, about 7 km from Lincoln; Oxford, a wet low fertility site on Ruapuna silt loam in the foothills of the Southern Alps; and near Taupo in the North Island on a light pumice soil. Cultivars used were OSR autumn “Flash” 2009-10, “Bravour” 2010-11 and spring “Ability”; BM ”Centennial” PC Accession “Beecher Field”; MF “Floral”; CS Accession no 4164.

Table 1: Soil Test Results 2009 with 2010 in brackets. All values except pH are MAF Quick Test values.

Site	Altitude (masl)	Soil type	pH	Olsen P	Ca	Mg	K	Na	S
Ashley Dene	35	Balmoral	5.8(5.6)	39(21)	10(9)	28(23)	12(8)	13(9)	20(26)
Oxford	290	Ruapuna	6.1(5.6)	4(5)	11(9)	17(15)	8(16)	5(4)	2(3)
Taupo	321	Pumice	5.7(5.6)	25(16)	5(5)	9(5)	8(4)	3(5)	76(56)

In 2009-10 treatments consisted of the five species sown in single blocks, either in the autumn or spring, and with nitrogen (N) treatments of either 50 or 150 kg N ha^{-1} applied at sowing. At Oxford, the N inputs were subplots of the species, and, at Ashley Dene, the high N plots also received 119 mm of irrigation across the growing season after the soil moisture deficit was greater than 50% of field capacity. This gave 20 plots per block, four replicates of the five species. Plot (or main plot) size varied with 3.5 m x 10 m plots at Taupo and 4.2 m x 10 m plots at Oxford and Ashley Dene. Sowing rates at all sites were: OSR 4 kg ha^{-1}, BM 4 kg ha^{-1}, PC 2.5 kg ha^{-1} (10.5 kg ha^{-1} Ashley

Dene autumn/winter, 5 kg ha^{-1} Taupo spring, CS 8 kg ha^{-1} (34 kg ha^{-1} Ashley Dene autumn/winter), MF 30 kg ha^{-1} sown on 5 June at Ashley Dene. Sowing dates were 5 May and 1 October at Ashley Dene and 11 June and 8 October at Taupo. At Oxford the site was too wet to sow in autumn and the first sowing was on 27 August and the second on 8 October. All sowing was done using an Oyjord cone seeder and sowing depths were approximately 1-1.5 cm. Autumn sowings of OSR and BM at Ashley Dene were destroyed by birds soon after emergence, and were resown on 25 June.

In 2010-11 there were fewer sowing dates. N treatments of 0, 50 or 150 kg N ha^{-1} were applied as urea. At Ashley Dene, N was applied on 31 August to autumn sown BM plots and on 16 September to autumn sown OSR plots. Autumn sown CS plots were abandoned due to premature death. N was applied to all spring sown plots on 23 November. At Oxford N was applied to reps 1 and 2 on 5 November and reps 3 and 4 on 10 November. MF and PC plots were abandoned at Oxford due to poor establishment and weeds. BM was not sown at Oxford because of space constraints. At Taupo N was applied on 8 November. At all sites the experimental design was a split plot with sowing dates as main plots and N levels as sub-plots. Ashley Dene plots were sown on 18 March and 14 September 2010, while at Oxford and Taupo sowing dates were 30 September and 31 August 2010 respectively. Again plots were sown using an Oyjord cone seeder at sowing depths of approximately 1-1.5 cm.

At all sites vegetation was initially controlled with glyphosate as Roundup Transorb® at 3 l ha^{-1} (a.i. 540 g l^{-1} glyphosate). Treflan® at 3 l ha^{-1} (a.i. trifluralin 480 g l^{-1}) was incorporated into the soil. Insect control was with diazinon granules at 800 g ha^{-1} (a.i. diazinon 200 g kg^{-1}) and Attack® at 1 l ha^{-1} (a.i. 25 g l^{-1} permethrin plus 475 g l^{-1} pirimiphos-methyl). After emergence plots were hand weeded if necessary.

Beehives were introduced at Ashley Dene (2 hives in 2009 and 4 hives in 2010) and Taupo (1 hive each year) at flowering to ensure pollination. At Oxford there were abundant bees in the adjacent beech forest

Final harvest usually occurred when the upper pods started to shatter. At Ashley Dene, some immature harvesting was required as severe gales destroyed bird netting prior to normal harvest time. At Taupo, resource issues resulted in harvest just prior to pod shattering. In 2009-10 seed yields were taken from 0.6-1.8 m^2 at Ashley Dene and Taupo and 0.6 m^2 at Oxford. In 2010-11 harvest area was 0.3 m^2 at Ashley Dene and 2.0 m^2 at Oxford and Taupo.

At final harvest, plants were harvested from each plot by hand using secateurs and quadrats. Samples were weighed fresh in both years. In 2009-10 subsamples were dried in a forced air oven at 65°C to a constant weight and used to determine harvest index. The remainder was dried in heated bins, then combined with the subsamples to determine seed yield. In 2010-11 a similar procedure was used with samples from plots at Oxford and Taupo, whereas at Ashley Dene the entire plot sample was hand threshed for seed yield and harvest index.

Oil was extracted mechanically using a cylinder hole screen press operating at a throughput of 20-35 g minute^{-1} with a choke size of 4 mm and operating temperature of 80°C. Sample size extracted was 250 to 300 g. Seed moisture content was determined at the time of extraction. Oil content is presented as extracted oil; this is oil obtained from the pressed seed, not including oil left in the cake.

All results except oil content and oil yield were analysed by ANOVA. Mean separation was through the use of Fishers protected LSD. Oil content and oil yield could not be analysed as to get enough seed for the press replicates were bulked. This was required as in some plots there was inadequate seed yield to obtain enough seed to press for oil. Meteorological data was collected from Hobo® microstations (Onset Computer Corporation, Bourne, Massachusetts) located at each site. Before the microstations were installed meteorological data and long term mean data were collected from the nearest NZ Meteorological Service stations. These were Broadfields (Ashley Dene), Taupo and Glentui (Oxford).

Results

Climate

The climate at the sites indicated that Ashley Dene was very dry with only 382 mm of rain during the 2009-10 growing season (from June to March) compared to the long term mean of 534 mm. For Oxford rainfall from August to March was 719 mm and for Taupo from May to March rainfall was 782 mm. Average temperatures over the growing seasons were: Ashley Dene 11.3°C, Oxford 12.3°C, Taupo 11.5°C. These values are very similar to long term means (LTM) as calculated from collected meteorological data.

In 2010-11 at Ashley Dene, mean temperatures were nearly identical to long term means. However, rainfall in winter (June to August) was 34% higher than the long term mean of 193 mm. During summer however, Ashley Dene received 152mm less rainfall than the long term mean. At Oxford, in 2010-11 temperatures during spring were equal to LTM's, but during January and February mean monthly temperatures were 1.9 and 1.4°C cooler than LTM's, respectively. Rainfall over the growing season was evenly distributed (total 519 mm) and nearly identical to the LTM of 513 mm. At Taupo mean monthly air temperatures were similar to LTM's early in the season but about 1 to 2°C warmer than LTM's from November to February. The most important climate results, however, were firstly the 209 mm rainfall at Taupo in January, 2011.This is nearly three times the long term January mean of 72 mm, and caused severe disease problems in harvested seed. Secondly, gale force winds on 24 December 2010 blew down bird netting at Ashley Dene, resulting in significant removal of seed by birds.

Germination and Establishment

Seed germination tests were carried out before sowing in both seasons and showed that while all germinations were greater than 80% in 2010-11, in 2009-10 both pennycress and meadowfoam had germination percentages of less than 80% (Table 2).

Survival

2009-10

The poor establishment of PC, and subsequent overrunning by weeds, led to its abandonment at all sites except the spring sowing at Ashley Dene. Red clover overran the October sown MF at Oxford.

2010-11

The March sowing of CS at Ashley Dene went prematurely to seed and died in the winter.

Table 2: Germination percentages of five species sown in a biodiesel experiment in two seasons.

Species	2009-10	2010-11
Brown mustard	81	84
False flax	95	96
Meadowfoam	76	94
Field penny-cress	79	94
Oilseed rape spring sown	97	91
Oilseed rape autumn sown	97	97

Total dry matter

2009-10

Total dry matter (TDM) production was highly variable (Table 3). In almost all cases the lowest TDM production was from Ashley Dene which had an overall grand mean of 2,564 kg ha^{-1}. Oxford and Taupo produced grand means of 5,485 and 4,555 kg ha^{-1} TDM respectively. Amongst the species OSR generally produced the highest TDM with nearly 10,000 kg ha^{-1} TDM produced at Oxford and over 7,000 kg ha^{-1} at Taupo. Both BM and CS also produced large amounts of TDM with maxima of over 7,000 kg ha^{-1} TDM for BM at Oxford and over 9,000 kg ha^{-1} TDM at Taupo. Averaged over all sites and species the high input treatments of 150 kg ha^{-1} produced 4,868 kg ha^{-1} TDM, while the low treatment produced 27% less (3,535 kg ha^{-1} TDM).

2010-11

Site TDMs in the second growing season were very similar to the first: spring Ashley Dene both around 2,500 kg ha^{-1} TDM, spring Oxford 5,990 kg ha^{-1} TDM, Taupo 4,700 kg ha^{-1} TDM (Table 4). OSR was the most productive species producing 6,100-6,800 kg ha^{-1} TDM at all sites except the September Ashley Dene sowing (3,257 kg ha^{-1} TDM) CS produced a similar yield to OSR at Oxford of 5,800 kg ha^{-1} TDM but considerably less at the other sites. Apart from possibly at Oxford, increased N appears to have no effect on TDM in 2010-11.

Seed yields

2009-10

Seed yield was extraordinarily variable over all sites, sowing dates and input levels (Table 3). At Ashley Dene MF produced up to 1,550 kg ha^{-1} of seed. However OSR, BM and CS produced mean seed yields of less than 900 kg ha^{-1}. At Oxford and Taupo, OSR achieved yields of up to 3,800 kg ha^{-1} and 2,300 kg ha^{-1} respectively and CS produced up to 1,400 kg ha^{-1} and 2,800 kg ha^{-1} respectively at the two sites. Overall OSR produced the highest seed yield of 3,778 kg ha^{-1} (Oxford) followed by CS at 2,915 kg ha^{-1} (Taupo) and BM at 2,078 kg ha^{-1} (Taupo). MF and PC did not perform well at any site because of poor establishment, weeds and disease. The response to N was inconsistent over sites and within sowing dates.

2010-11

Seed yields in the second growing season were not affected by any of the treatment combinations at each site (Table 4). However, lowest yields averaged across species and N occurred at Taupo (316 kg ha^{-1}) with Oxford and Ashley Dene producing 1,793 kg ha^{-1} and 943 kg ha^{-1} respectively. Seed yield response to N was again inconsistent in 2010-11 (Table 4) except at Oxford. At this site seed yields of both OSR and CS increased as the level of

N applied increased. At the other two sites, the response was variable.

Harvest index

Note that the harvest indices were measured on a small subsample of the harvested crop and may not agree with that calculated from the main sample, which had some harvest losses.

2009-10

Harvest indices were low ranging from 4% to a maximum of 35%. This suggests that considerable seed was lost prior to harvest (Table 3).

2010-11

Harvest indices were again variable as in the first growing season, ranging from 1% up to 30% (Table 4).

Thousand seed weight

2009-10 and 2010-11

Thousand seed weights were highly variable between species, as would be expected, but much less variable between sites and seasons. However at Ashley Dene and Taupo thousand seed weight of OSR in the spring sowings was much less than in the autumn sowings. In the second season, thousand seed weights were lower than in the first season.

Oil content

2009-10

In the first growing season, expelled oil content was highest in OSR, averaging 40%. Oil contents of BM and CS were similar at 35% and 33% respectively. Meadow foam had a mean oil content of 15% and PC 24 %.

2010-11

At Ashley Dene and Oxford oil contents in the second growing season were similar to the previous year. However, oil content was much lower at Taupo than in the previous year with all three species producing less than 24% oil content.

Oil Yields

2009-10

Oil yields (Table 3) between species showed very similar trends to seed yields with the exception of MF. This species produced the highest seed yield (1,551 kg ha^{-1}) at Ashley Dene, but, because of its low expelled oil content, it only produced 322 kg of oil ha^{-1}. OSR produced up to 326 kg oil ha^{-1} at this site from a very poor crop badly affected by bird damage. OSR produced maximum oil yields ha^{-1} from the spring sown high input (1,518 kg ha^{-1}) and low input (1,102 kg ha^{-1}) treatments at Oxford. OSR and CS also produced oil yields over 900 kg ha^{-1} at Taupo with BM producing over 700 kg ha^{-1} from autumn sown high input plots. PC and MF produced under 200 kg ha^{-1} of oil at Taupo.

2010-11

In the second growing season oil yields were very poor, with no crops producing in excess of 1,000 kg oil ha^{-1} (Table 4). At Oxford OSR did produce up to 967 kg oil ha^{-1}, but CS only reached a maximum of 705 kg oil ha^{-1}.

Table 3: Total DM yield, seed yield, harvest index, thousand seed weight, oil content and oil yield at final harvest of five species at three sites in 2009-10 sown in autumn-winter or spring with low or high inputs.

Site	Ashley Dene				Oxford				Taupo			
Sowing date	May[1]		October		August		October		June		October	
Nitrogen kg ha^{-1}	50	150[2]	50	150[1]	50	150	50	150	50	150	50	150
					Total DM yield (kg ha^{-1})							
OSR	2737	4030	2285	3145	7033	8105	6560	9863	3682	6728	4169	7114
BM	2580	3923	1536	3288	4976	7100	4244	6582	4337	5065	5205	3882
CS	2364	3731	1820	3125	3630	5736	4144	4112	4892	4077	3928	9890
MF	2982	3795	381	1066	2364	1519	-	-	2021	1827	4074	3263
PC	-	-	532	1425	-	-	-	-	-	-	2751	-
Significance	NS	NS	**	***	**		NS		**	*	*	**
LSD[3]	426	1573	875	897	1136 (1472)		2559 (2556)		1490	2510	1431	2806
					Seed yield (kg ha^{-1})							
OSR	767	823	320	369	1540	2448	2664	3778	885	2304	1059	1661
BM	112	201	515	619	1154	1577	1158	1950	1421	2078	595	952
CS	303	601	492	902	1087	1105	1433	1426	1065	1397	1361	2915
MF	869	1551	107	143	622	401	-	-	683	476	966	754
PC	-	-	253	288	-	-	-	-	-	-	751	-
Significance	***	**	**	**	**		NS		**	**	**	***
LSD[3]	207	631	178	327	336 (312)		917 (782)		298	787	376	878
					Harvest index (%)							
OSR	19	17	10	4	19	28	28	30	19	24	24	27
BM	4	4	26	26	25	26	25	26	28	32	26	21
CS	8	10	33	30	30	24	32	25	31	37	27	32
MF	22	20	21	11	30	27	-	-	35	30	24	25
PC	-	-	36	23	-	-	-	-	-	-	27	-
Significance	**	**	***	***	**		NS		**	*	NS	**
LSD[3]	8.1	7.5	7.9	8.5	5.0 (6.4)		7.1(6.2)		8.1	7.7	9.0	5.4
					Thousand seed weight (g)							
OSR	5.0	5.0	2.5	2.8	4.3	5.3	4.8	4.1	4.0	4.6	2.8	3.2
BM	1.3	1.8	2.1	2.3	2.8	3.1	2.8	2.8	2.7	3.2	2.4	2.6
CS	1.0	1.4	1.3	1.1	1.4	1.5	1.5	1.4	1.4	1.9	1.2	1.2
MF	6.9	7.6	4.2	4.7	4.4	6.3	-	-	6.0	6.7	7.9	6.6
PC	-	-	0.8	0.9	-	-	-	-	-	-	1.0	-
Significance	***	***	***	***	NS		*		***	**	***	***
LSD[3]	0.16	0.31	0.44	0.49	2.37 (2.59)		0.37 (0.31)		0.39	1.66	0.43	0.33
					Expelled Oil content (g 100 g^{-1})							
OSR	40.4	39.6	40.5	31.7	41.9	38.2	41.4	40.1	44.1	43.3	43.7	41.0
BM	-	-	30.7	29.9	36.8	33.6	35.1	32.9	-	36.9	36.7	38.6
CS	31.6	33.8	29.4	30.0	34.9	32.8	33.7	33.0	36.0	32.4	38.2	34.3
MF	20.5	20.8	5.9	5.9	14.5	14.5	19.1	19.1	15.4	13.1	15.6	15.6
PC	-	-	23.5	23.4	23.7	20.1	-	-	-	28.4	25.5	-
					Oil Yield (kg ha^{-1})							
OSR	309	326	130	117	645	935	1102	1515	390	998	463	681
BM	-	-	158	185	424	530	406	641	-	767	218	367
CS	96	203	145	271	379	362	482	471	383	453	520	966
MF	178	322	6	8	90	58	-	-	105	62	151	118
PC	-	-	59	67	-	-	-	-	-	-	192	-

NS = non significant *, **, *** = significant at 0.05, 0.01, 0.001 respectively. [1]OSR and BM were resown on 25 June. [2]also received 119 mm of irrigation. [3]Unbracketed LSD is within species (Bracketed LSD is for all other comparisons).

Table 4: Total dry matter, seed yield, harvest index, thousand seed weight, oil content and oil yield at final harvest of three species at three sites in 2010-11 with varying sowing dates and a range of nitrogen application rates.

Site:	Ashley Dene				Oxford			Taupo		
Sowdate:	March		September		September			August		
N kg ha^{-1}	50	150	50	150	0	50	150	0	50	150
Species	Total dry matter (kg ha^{-1})									
OSR	7112	6600	3140	3373	5416	5987	7047	7235	6459	6803
BM	2828	2718	2067	2356	-	-	-	3301	3934	3208
CS	-	-	2214	2208	5049	5559	6852	3594	4465	3509
Significance	NS		NS		NS			NS		
LSD[1]	1388 (1041)		415 (472)		1432 (1423)			1923 (1717)		
	Seed yield (kg ha^{-1})									
OSR	1640	1490	413	505	1646	1928	2285	498	274	381
BM	335	307	417	455	-	-	-	61	121	142
CS	-	-	257	315	1264	1605	2032	440	551	376
Significance	NS		NS		NS			NS		
LSD[1]	326 (755)		90 (267)		330 (331)			207 (387)		
	Harvest index (%)									
OSR	22	22	13	14	27	26	27	7	2	7
BM	12	12	20	19	-	-	-	1	3	4
CS	-	-	12	14	24	27	30	13	13	9
Significance	NS		*		*			*		
LSD[1]	2.4 (6.8)		1.7 (7.2)		2.9 (2.7)			4.3 (6.0)		
	Thousand seed weight (g)									
OSR	2.0	2.0	2.4	2.3	3.4	3.2	3.2	2.9	2.4	2.9
BM	0.5	0.4	1.6	1.6	-	-	-	1.9	1.5	1.8
CS	-	-	0.9	0.9	1.3	1.3	1.3	0.9	0.9	0.9
Significance	NS		NS		NS			NS		
LSD[1]	0.40 (0.42)		0.18 (1.06)		0.21 (0.22)			0.56 (0.85)		
	Oil content (g 100 g^{-1})									
OSR	42.7	41.4	41.6	36.9	46.3	45.1	42.3	23.8	23.1	22.3
BM	31.5	32.9	29.0	28.0	-	-	-	12.1	12.1	12.1
CS	-	-	28.14	28.1	36.9	33.9	34.7	23.4	23.4	21.3
	Oil yield (kg ha^{-1})									
OSR	700	617	172	186	762	870	967	119	63	85
BM	105	101	121	127	-	-	-	7	15	17
CS	-	-	72	89	466	544	705	103	129	80

NS = non significant *, **, *** = significant at 0.5, 0.01, 0.001 respectively. [1]Unbracketed LSD is within species Bracketed LSD is for all other comparisons.

Discussion

These results indicate that there are some species of oilseed plants capable of producing over 1,000 kg oil ha^{-1} in marginal environments. In particular, OSR, CS and BM produced oil yields in excess of 1,000 kg ha^{-1} on low fertility soils in Oxford and Taupo.

The European Union produced approximately 68% of the world's biodiesel in 2008 and OSR was the feedstock for 84% of this (Malca and Freire, 2011). OSR has yielded over 3 t seed ha^{-1} in N and irrigation trials (Daly and Martin, 1988). With new cultivars and similar good husbandry, over 4 t ha^{-1} of seed have been harvested commercially (Ashley Pace, Biodiesel NZ, pers. comm., 2011). In our trials OSR proved to be a highly adaptive crop which performed well at Oxford and Taupo, especially under high inputs (Table 3). At Ashley Dene, which received about half the rainfall of the other two sites, yields were considerably lower, autumn sowings producing 800 and spring 300 kg seed ha^{-1}.

The major problem with OSR was bird damage, at the seedling stage at Ashley Dene and at all sites during seed fill. This latter difficulty necessitated the netting of all trials. Birds are also a problem in commercial crops and have been observed by the authors eating seed over 100 m into commercial crops in Canterbury.

BM and CS gave similar oil yields to OSR at Ashley Dene and Taupo (Tables 3 and 4) These two crops have similar seed yields and harvest indices to OSR, but seed size and seed oil content were lower for these two crops compared to OSR. Small seed size and oil content increase processing and transport costs for commercial biofuel production.

In the UK maximum seed yields of BM have reached 2.2 t ha^{-1} (Meakin, 2007). However, in the present trials BM seed pods shattered easily and the crop also suffered from white rust (*Albugo candida* (Pers.) Kuntze) during the vegetative growth phase in 2010-11 and bird damage during seed fill. So BM did not appear to have enough advantages over OSR to continue with it at all sites in 2010-11. While swathing may have helped reduce shattering, this was not possible in these small plots.

CS did not appear to have suffered much bird damage in these trials, which would be a great advantage for a commercial crop in New Zealand. Also it matures up to a month earlier than OSR. It therefore may have a place as a short season crop to include in a rotation. CS is being grown in USA and Canada as a short season low input biofuel crop (Pilgeram *et al.*, 2007) and yields overseas have been as high as 2.5 t ha^{-1} under highly fertile conditions and up to 1.7 t ha^{-1} under low fertility conditions (Meakin, 2007).

MF has been grown commercially on good quality land in New Zealand (SouthlandNZ, 2011). When sown in the autumn, it yielded well on the droughty Ashley Dene site, but not at the other sites where weed competition over grew this low growing crop. Seed weights were high but oil extraction and yields were very low, so work on this crop was not continued.

PC failed to establish at most sites and is known as a shy establisher (Schill, 2008). This will make it unsuitable for a biodiesel crop on marginal lands as weeds are likely to be a major threat to crop establishment and growth.

Yields were highest under high inputs at Oxford and Taupo and lowest at Ashley Dene under low inputs. These oilseed crops are unsuitable for drought prone paddocks and will need to be grown in fertile soils without water stress in order to produce consistently high yielding crops with high concentrations of oil. Seed yields from these two seasons compare very favourably with yields reported from overseas. Pavlista *et al.* (2011) reported that in Nebraska, USA production ranged from 402 to 2,261, 398 to 1,277 and 556 to 1,456 kg ha^{-1} for OSR, BM and CS respectively.

In the first year, yields were affected by a range of issues. While the seeds had reasonable germination rates (Table 2) populations were highly variable (data not shown). Most of these species have very small seeds, e.g. thousand seed weight of sown seed of OSR, BM, CS, MF and PC were 3.25g, 2.5g, 1.3g, 63g and 0.89g respectively in 2009 (Table 3). This makes sowing depth critically important. Lamb and Johnson (2004) found that increased sowing depth of OSR generally had a negative effect on seed emergence and they recommended sowing no deeper than 25 mm. While our sowing depth was set at approximately 10 mm, this was difficult to maintain on our marginal soils which contained stones (Ashley Dene), pumice (Taupo) or were wet and infertile (Oxford).

In the second year, extreme weather events affected two of the trial sites. Very high rainfall caused disease problems at Taupo, while gale force winds nearly destroyed all of the bird netting at Ashley Dene. Both events led to severe seed loss and hence reduced yields. This is a good indication of the increased risks arable farmers face growing oilseed crops on marginal sites.

Conclusions

There are some important conclusions which can be drawn from this work:

(1) OSR is an adaptive species that can perform well in difficult conditions.
(2) OSR is highly susceptible to bird damage.
(3) Both BM and CS are capable of producing similar yields to OSR at some sites.
(4) BM is susceptible to shattering.
(5) CS is much less susceptible to bird damage, is faster maturing than OSR and BM and is a highly promising candidate for biodiesel production in New Zealand on marginal soils.
(6) However, for consistently high yields and high oil concentrations these crops will require fertile soils or high inputs.
(7) Low growing crops and poor establishers such as MF and PC are unsuitable for marginal sites.
(8) Response to N is variable and may not be economic on some sites.

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