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The effect of harvest date on the yield and mineral content of *Phalaris arundinacea* L. (reed canary grass) genotypes screened for their potential as energy crops in southern England

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Abstract: The effect of harvest date on dry matter production per hectare and moisture content of 13 genotypes of *Phalaris arundinacea* (reed canary grass) was studied between 1995 and 1998 and N, P and K concentration in biomass was measured in 1998. There were two winter harvests, the first at crop senescence and the second after a subsequent delay of several weeks which varied each year. Average dry matter production was higher at the first (conventional) harvest than at the delayed harvest except in 1996. Each year there were differences in yield between genotypes and some differences were significant. Delayed harvest reduced yield by an average of 24% in 1997 and 23% in 1998 when losses resulted from 48% loss of leaf and 16% of stem matter. Delayed harvest decreased moisture content by 50% in 1997 and 52% in 1998 but it was 49% higher in 1996. In 1998, delayed harvest did not reduce N concentration in all genotypes and the reduction of P was variable, but K concentration was reduced by an average of 54%. Results indicate the suitability of reed canary grass as a biofuel, and variability between genotypes offers potential for crop improvement through selection and breeding.

Keywords: *Phalaris arundinacea*; biomass; energy crop; yield; mineral content

INTRODUCTION

Phalaris arundinacea L. (reed canary grass), subsequently called RCG, is a coarse, vigorous, rhizomatous perennial grass distributed throughout Europe and in temperate regions of North America and Asia. The grass is tall (60–200 cm) and leafy but its agricultural value is limited to the young succulent shoot stage; old stems are less palatable to livestock,[1–3] and it is little used in the UK because of its low potential as a forage species.[4] In natural conditions it is most commonly found growing along water margins,[1,5] but when established it has drought resistance.[6] Early trials showed that it is tolerant of a range of soil textures from silty loam to heavy clay.[7] Because RCG has a wide geographic adaptation, genetic variation is present that can be used to select genotypes for specific environments. Adaptability and high yield[4] led to RCG being evaluated as a potential bioenergy crop for the UK.[8]

For a species to be considered as an energy crop it requires high yield potential with high dry matter content at harvest. It should require little cultivation, few nutrients or crop protection chemicals, and the biomass should have a low concentration of minerals to make it suitable for combustion in a modern power generation plant. Low mineral content in biomass at harvest has been shown to improve combustion characteristics.[9] In Sweden, delaying harvest until the early spring instead of harvesting as soon as possible after stems had senesced was shown to significantly improve dry matter content and reduce mineral content of the biomass, although yield was less than from an earlier harvest; biomass quality benefited from the cold and dry conditions during the winter.[10] Because winter conditions in the UK are wetter and milder than Scandinavia, weather effects on yield and quality of the biomass may be different. In studies of switchgrass (*Panicum virgatum*) and *Miscanthus* genotypes, which are also potential bioenergy crops, delayed harvest reduced yield and mineral content of crops grown at the same location.[11,12]

Perennial grasses such as RCG may have potential in the future as raw materials for fibre production for paper making and a source of cellulose for the production of ethanol as a liquid biofuel.[13]

In our study we (a) measured the yield per hectare and moisture content of 15 genotypes of RCG at two harvest dates in winter over four years, and (b) measured the nitrogen, phosphorus and potassium

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content at both harvests in the final year of the experiment. The study reported here formed part of a larger project to develop RCG for energy and industrial use in Northern Europe, in which 14 accessions from breeding lines in Europe and a commercial variety from the USA were evaluated at nine sites in Northern Europe.[14]

MATERIALS AND METHODS

Site and preparation of field experiment

The experiment was conducted between 1995 and 1999 at Rothamsted Research Farm in southeast England (Latitude 51°48′ 30″ N, 0°48′ 10″ W, altitude 128 m). The soil is a flinty, silty, clay loam over clay-with-flints mapped as Batcombe series.[15] The topsoil, 0–23 cm, contains about 23% clay and has a pH in water of 7. The USDA classification of the soil is Aquic Paleudalf[16] and the FAO classification is Chromic Luvisol.[17]

The experiment comprised 15 genotypes of RCG; the geographic origin of each is given in Table 1. Seed was germinated in Petri dishes lined with a Whatman GF/AS glass microfibre filter (Whatman International, Maidstone, UK) laid on top of two Whatman no. 2 filter papers. The filter papers were moistened with a 0.2 g L^{-1} KNO_3 solution. Dishes were covered and placed in a growth cabinet at 20 °C and received 16 h light and 8 h darkness. When seedlings had shoots approximately 2 cm long they were transferred singly into peat pots filled with suitable general-purpose compost. Pricking out seedlings took place about one month after germination and was completed on 21 April 1995. Seedlings were grown on in an unheated greenhouse until they had approximately five tillers and then were transferred to caged areas at ambient temperature to harden off for 14 days before planting in the field. All genotypes except genotype 14 (G) were planted in the field on 23 May 1995. G14, which had been slower to germinate compared to the others, was planted on 6 June 1995. Details of agronomic treatments applied during the course of the experiment are presented in Table 2.

Plots were 3.75 m^2 in area and contained 60 plants spaced at 25 cm × 25 cm. Plots of each genotype were randomised in each of six replicate blocks. Harvest took place after the end of the growing season. Three blocks were randomly selected for the first harvest (conventional) and the other three for the second harvest (delayed). Blocks assigned to the conventional or late harvest remained the same for the duration of the experiment.

Table 1. Names and geographic origins of the genotypes of reed canary grass used in the study

Genotype	Source/name	Geographic origin
1	SWN RF9208	Poland
2	SWN RF9214	Russia
3	SWN RF9401	Northern Sweden
4	SWN RF9405	Northern Sweden
5	SWN RF9406	Northern Sweden
6	SWN RF9407	Northern Sweden
7	SW RF5001	Selection in RF8701
8	SW RF5002	Hungary
9	SW RF5003	Selection from Russian population
10	SW RF5004	Various[a]
11	SW RF8701	Sweden
12	Palaton[b]	USA
13	Jo 0510	Finland
14	LEU 94201	Germany
15	LEU 94101	Germany

[a] Selected in populations from Switzerland, Portugal and former Yugoslavia.
[b] Commercial variety.

Plant assessments

In 1995, stem number and stem height were measured on five plants per plot 11 weeks after planting and ground cover scored on individual plots 21 weeks after planting. In 1996 and 1997, the date when the first flowers completely emerged from the flag leaf sheath was recorded as the start of flowering. The number of flowering stems was estimated as the percentage of all stems present and plots were scored on three occasions at seven-day intervals in 1996 and five occasions in 1997. Stem height was measured in August 1995 and July 1996 and 1997. In 1996, 1997 and 1998, measurement coincided

Table 2. Details of main agronomic treatments and harvest dates

Fertilizer and plant protection	1995	1996	1997	1998
Nitrogen (kg ha^{-1})	50	120	120	100
Phosphate (kg P ha^{-1})	–	29	29	29
Potassium (kg K ha^{-1})	–	90	90	90
Pesticides				
Chlorpyrifos				8 May, 600 g ai ha^{-1}
Dimethoate			13 May, 680 g ai ha^{-1}	27 July, 680 g ai ha^{-1}
Mecoprop-P		13 May, 1500 g ai ha^{-1}		27 April, 1200 g ai ha^{-1}
Bromoxynil/ioxynil	19 July, 100:100 g ai ha^{-1}	13 May, 280:280 g ai ha^{-1}		
Fluroxypyr				22 May, 200 g ai ha^{-1}
Harvest				
Conventional	28/2/96	7/1/97	4/12/97	21/12/98
Delayed	–	5/2/97	29/1/98	3/2/99

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with flowering. Height measurement was made from the soil surface to the ligule of the last emerged leaf. This method of measurement underestimates final stem height by about 20% but avoids variation due to the stage of stem extension following flower emergence.[18]

Harvest and mineral analysis

In 1995 all plots were harvested at the conventional time because plants were small and immature. Although G3 and G4 had been successfully transplanted in the spring, they failed to thrive and no yield for them was recorded in 1995; subsequently these genotypes were omitted from the experiment. The conventional harvest was taken at the first opportunity after senescence and the delayed harvest took place after a subsequent period of weeks which varied each year (Table 2).

The central strip of each plot was mechanically harvested to leave a 5 cm stubble. Harvest area was 73% of the plot. The cut crop was collected and bagged and taken to the laboratory for fresh weight determination. A subsample was taken from each plot sample, dried at 80 °C and dry matter determined. In 1998 samples were separated into leaf and stem components before drying and weighing and then milled to pass through a 1 mm screen before chemical analysis.

N content was determined with a LECO CNS 2000 combustion analyser (LECO Instruments (UK) Ltd, Stockport, UK). Phosphorus and potassium were determined, following digestion in nitric and perchloric acid, using inductively coupled plasma emissions spectrometry (ICPES).

Statistical analysis

Results presented in the tables were analysed for significant differences by analysis of variance (ANOVA) using GenStat.[19] Significant differences among samples are reported at the 0.05 significance level.

RESULTS

Crop development

There were large differences between genotypes in stems per plant when measured 11 weeks after planting (Table 3). The stem number of G14, which as a seedling was slower to develop than the others, was close to the average whereas some of the other genotypes planted a week earlier had fewer tillers. G3 had the fewest stems and the difference was statistically different from most of the other genotypes (Table 3). At the time stem counts were made, stem height ranged from 10.9 to 55.6 cm and some differences were significant. G3, G4 and G6 had the shortest stems and G7 and G10 the tallest. By October many genotypes had total ground cover but G3, G4, G6 and G12 had spread very little (Table 3). Variability was evident within genotypes because, even where achieved, total ground cover was not present on all replicate plots. In 1996, G12 had the shortest stems and the difference from the others was statistically significant; G12 had short stems in 1997 and, unlike most other genotypes its height was the same as in the previous year whereas others were slightly shorter; some of the differences between genotypes were significant. In 1998, stems were shorter than in the previous two years and G6 was significantly shorter than all other genotypes; no comparison between other genotypes was significant.

Table 3. Stem number, height and plant cover in 1995 and stem height in 1996–1998

	1995			1996	1997	1998
Genotype	Stems (per plant)	Height (cm)	Total soil cover (plots)	Height (cm)	Height (cm)	Height (cm)
1	24.0	49.0	5/6	167.6	160.8	146.6
2	22.5	45.5	4/6	166.7	154.4	139.8
3	16.2	10.9	0/6	–	–	–
4	20.1	11.6	0/6	–	–	–
5	21.7	44.0	5/6	165.8	164.1	142.6
6	18.2	22.1	1/6	160.2	155.9	122.8
7	20.0	55.6	6/6	175.3	169.7	149.2
8	21.8	51.0	6/6	165.1	152.4	146.4
9	24.2	43.7	4/6	171.1	164.3	146.2
10	20.8	54.8	6/6	171.4	161.6	150.4
11	20.8	51.5	6/6	171.8	162.9	147.3
12	17.5	42.5	1/6	150.7	151.3	141.4
13	25.7	39.9	4/6	168.6	159.5	145.7
14	19.1	35.0	6/6	168.1	150.7	140.7
15	21.6	45.3	6/6	167.9	157.7	149.1
Mean	21.0	40.2		167.1	158.9	143.7
LSD	4.6	8.2		8.8	8.6	11.9
d.f.	70	70		60	60	60

In March 1997 some shoots were seen to be dying, caused by stem-boring larvae. On the basis of one successful hatch of a larva the species was identified as *Apamea ophiogramma* Esper (double-lobed moth), but we do not exclude other species of stem borer being present since eggs found in the crop in November 1997 fitted the description of the family Chloropidae, of which some are known to attack RCG, i.e., the frit fly (*Oscinella frit*) (S Hellquist, personal communication). The shoot damage observed closely resembled frit fly damage in cereals. In March 1998, dead shoots were again evident in larger amounts and on average 68% of shoots were dead. By May most genotypes had a greater number of shoots than in March (data not presented). Late-developing shoots that are not vernalised remain vegetative and as a result contribute less to biomass yield.

The first flowers were recorded in June 1996 on G8, G14 and G15. All genotypes flowered within 14 days except G6, which flowered about a week later (Table 4). In 1997 flowering started in late May but only on G12, G13, G14 and G15. Full flower emergence took 28 days, except G6, G8 and G13; G8

Table 4. Emergence of flowers scored as a percentage of stems present, 1996–1998 (rounded values)

	1996		1997		1998
Genotype	First flower emergence, 3 June	Flower emergence 17 June	First flower emergence, 21 May	Flower emergence 18 June	Flower emergence 10 June
1	0	100	0	100	20
2	0	100	0	100	30
5	0	100	0	20	10
6	0	<1	0	10	0
7	0	100	0	100	10
8	<1	100	0	80	20
9	0	100	0	100	15
10	0	100	0	100	10
11	0	100	0	100	10
12	0	100	10	100	15
13	0	100	10	90	20
14	<1	100	20	100	30
15	<1	100	10	100	30

and G13 were almost at full emergence at this time but there were few flowers on G6. Flowering started at the beginning of June in 1998 with flowers present on all genotypes except G6; a date for full emergence was not recorded.

Biomass yield: conventional harvest

Mean harvestable dry matter yield of all genotypes was low in the establishment year (1995), substantially higher in 1996 and 1997 and slightly lower in 1998 than in 1997; however, some genotypes had improving yields in 1998 (Table 5). In 1996 average yields from the conventional and delayed harvests were the same, probably as a result of the closeness of the harvest dates, and the data has been combined for interpretation. Each year there were large yield differences between genotypes and some differences were statistically significant. Genotypes producing high yields at the beginning of the study remained amongst the highest yielding at the end, but there were year-to-year changes in ranking. G6 had the lowest yield every year and in 1998 produced only 48% of the yield of the best-yielding genotype that year (G15). Between 1996 and 1998 G1 produced the most biomass, which is important in commercial terms, but its cumulative yield was not statistically different from others except G6, G9 at the conventional harvest, and G12. Yield in 1998 may have been reduced as a result of stem borer damage but the effect could not be measured.

Table 5. Dry matter yields ($t\,ha^{-1}$) at the conventional and delayed harvest, 1995–1998

			1997		1998		1996–1998[b]		
Genotype	1995	1996[a]	Conventional	Delayed	Conventional	Delayed	Conventional	Delayed	cv (%)[d]
1	2.18	9.20	10.22	7.00	11.53	7.45	31.39	23.70	11.4
2	1.56	9.01	10.04	6.90	8.68	7.43	27.41	23.66	16.6
5	1.38	8.29	9.30	6.44	9.07	7.30	26.90	21.78	6.8
6	0.40	5.75	6.39	5.06	6.11	5.37	18.25	16.19	15.5
7	2.03	9.45	10.33	6.46	11.11	8.80	31.15	24.45	10.4
8	2.17	9.35	9.50	9.29	9.87	8.56	28.50	27.42	16.2
9	1.39	8.03	8.51	7.15	8.04	6.27	24.01	22.01	12.5
10	1.98	8.46	10.05	8.91	10.00	6.58	28.79	23.67	10.0
11	1.79	8.96	10.44	7.99	7.29	6.17	26.64	23.15	9.8
12	1.41	6.73	8.98	6.19	7.91	5.54	24.55	17.52	23.0
13	1.46	8.11	9.97	7.19	8.67	6.96	26.92	22.07	7.4
14	1.24	8.64	10.06	7.46	8.87	8.19	28.00	23.86	3.7
15	1.60	7.50	9.53	8.15	11.73	6.55	27.18	23.77	14.4
Mean	1.58	8.27	9.49	7.25	9.14	7.01	26.90	22.52	
Harvest × genotype LSD				2.04		3.20		5.18	
d.f.				41		52		46	
Harvest time LSD[c]	0.60	2.12		1.87		3.18		4.89	
d.f.	58	48		48		48		48	4

[a] Mean value for conventional and delayed harvest.
[b] Values for 1996 separated for harvest times.
[c] For comparisons with the same harvest date.
[d] Coefficient of variation of each variety analysed separately for 1996–1998 for conventional and delayed harvests.

Table 6. Leaf and stem dry matter ($t\,ha^{-1}$) at the conventional and delayed harvest in 1998

	Leaf		Stem	
Genotype	Con-ventional	Delayed	Con-ventional	Delayed
1	3.01	1.13	8.52	6.32
2	2.09	0.83	6.59	6.59
5	2.24	0.72	6.83	6.58
6	1.89	1.07	4.22	4.30
7	2.54	1.71	8.57	7.09
8	2.11	2.06	7.76	6.50
9	1.35	0.52	6.68	5.75
10	2.20	1.47	7.80	5.11
11	1.51	0.65	5.77	5.51
12	1.25	0.58	6.66	4.97
13	1.94	0.80	6.73	6.16
14	1.94	1.47	6.93	6.72
15	2.63	0.81	9.10	5.74
Mean	2.06	1.06	7.09	5.95
Harvest × genotype LSD		0.93		2.63
d.f.		50		52
Harvest time LSD [a]		0.91		2.63
d.f.		48		48

[a] For comparisons with the same harvest date

Delayed harvest

Mean yield was less than from the conventional harvests except in 1996. In 1997 and 1998 differences were similar, being respectively 24% and 23%. Yield loss mainly results from stem and leaf detachment; partitioning biomass into leaf and stem components in 1998 showed that both leaf and stem losses varied considerably between genotypes but on average more leaf was lost (48%) than stem (16%) (Table 6). At both harvest times there were genotypes with a heavier yield than the only commercial genotype (G12). However, this genotype was developed for conservation purposes and not as a biofuel crop.

Biomass quality

In 1996 moisture content was lower at the conventional harvest than at the delayed by an average of 49% (Table 7). In subsequent years biomass of all genotypes was harvested drier at the delayed harvest, averaging 50% less moisture in 1997 and 52% in

Table 8. Moisture content ($g\,kg^{-1}$) of leaves and stems at the conventional and delayed harvest in 1998

	Leaf		Stem	
Genotype	Con-ventional	Delayed	Con-ventional	Delayed
1	54.5	13.3	60.9	21.5
2	31.4	12.8	49.9	28.8
5	25.4	9.8	49.4	26.9
6	38.7	4.5	49.3	21.0
7	34.1	25.4	51.6	31.1
8	33.5	16.2	56.8	41.1
9	17.8	19.6	39.5	22.5
10	23.4	18.8	51.1	42.2
11	18.3	13.7	48.4	27.2
12	14.7	8.9	43.6	24.8
13	29.5	23.3	52.1	27.6
14	28.4	14.7	50.6	35.9
15	23.6	9.4	50.5	23.7
Mean	28.7	14.6	50.3	28.7
Harvest × genotype LSD		19.4		13.4
d.f.		41		36
Harvest time LSD[a]		17.8		12.0
d.f.		48		48

[a] For comparisons with the same harvest date.

Table 7. Moisture content ($g\,kg^{-1}$) of biomass at the conventional and delayed harvest, 1995–1998 (rounded values)

	1995	1996		1997		1998	
Genotype	Conventional	Conventional	Delayed	Conventional	Delayed	Conventional	Delayed
1	27	21	42	54	38	55	20
2	26	18	45	59	32	61	27
5	33	21	42	53	26	54	25
6	27	18	35	64	26	55	18
7	32	23	39	54	24	57	29
8	28	23	40	60	29	62	37
9	27	20	37	47	24	52	22
10	33	23	46	55	26	59	28
11	32	20	39	58	27	55	26
12	27	19	47	51	23	46	23
13	27	21	44	59	30	58	27
14	36	26	39	60	29	67	33
15	31	23	41	58	28	52	22
Mean	31	21	41	56	28	56	27
Harvest × genotype LSD			9.0		13.3		13.2
d.f.			44		35		52
Harvest time LSD[a]	6.0		8.4		11.8		13.0
d.f.	58		48		48		48

[a] For comparisons with the same harvest date.

1998. At each harvest there were some statistically significant differences in moisture content detected between genotypes (Table 7). Leaf and stem moisture content were measured separately in 1998 and both components were drier at the delayed harvest except for one genotype (Table 8). Moisture content varied considerably between genotypes at both harvests, with some differences being statistically significant. The average loss of moisture by late harvest was 49% for leaf matter and 43% for stems.

In 1998, at the conventional harvest, nitrogen concentration in biomass ranged from 0.65% to 0.94% and at the delayed harvest it was between 0.59% and 0.88% (Table 9). By delaying harvest, N concentration fell by an average 8% but differences ranged from 3% to 30%. Four genotypes had increased N concentration at the delayed harvest (range 3–18% increase). At both harvest times some differences between genotypes were significant and there were some significant interactions between harvest date and genotype.

Phosphorus concentration declined by an average of 23% by the delayed harvest for all genotypes except G5, where a slight increase of <1% was recorded (Table 9). Like N concentration, large differences were found in P concentration between some genotypes and some differences were statistically significant. Potassium concentration was reduced in all genotypes by an average of 54% (range 8–76%) by delaying harvest (Table 9). At both harvests differences between some genotypes were significant and there were interactions between genotype and harvest date.

DISCUSSION

Growth

All genotypes began to flower at the same time in 1996 except for G6, but flowering date was more variable in 1997 and 1998. Leaf development stops at flowering but maximum biomass is not reached until after seed ripening.[18] Senescence begins after seed ripening, but RCG leaves can remain green for several months after flowering.[20] Flowering was found to extend over several weeks, which is in accordance with findings elsewhere[18,21] and probably results from differences in stem age affecting the time to reach full crop maturation. Straw stiffness is poor and early-maturing stems may lodge or break, causing loss of biomass and poor crop drying. Breaking stems has also been identified as the cause of regrowth from nodes lower down the stem[22] and regrowth of this type can also delay maturation. The difference in the date of the conventional harvest from early December to late February is probably influenced by environmental conditions and, in particular, accumulated temperature.[18] In the autumn the date that frosts begin may also influence the time to complete senescence but the effect of frost on senescence requires detailed investigation.

RCG has good winter hardiness and the genotypes in this study did not have a period of dormancy, whereas dormancy is a normal characteristic of RCG growth in Scandinavia.[14] Lack of dormancy resulted in green shoots being present in the understorey during autumn and winter. This has also been reported in crops in the USA.[23] Harvest must occur before new shoots elongate otherwise the biomass harvested will have lower dry matter and higher mineral content.

Table 9. Nitrogen concentration (%DM), phosphorus and potassium concentration (mg kg^{-1}) in dry matter at the conventional and delayed harvest in 1998
Offtakes (kg ha^{-1}) are given as rounded values in brackets

	Nitrogen		Phosphorus		Potassium	
Genotype	Conventional	Delayed	Conventional	Delayed	Conventional	Delayed
1	0.90(104)	0.72(53)	649(8)	454 (3)	4207 (49)	1412(10)
2	0.76(66)	0.74(56)	560(5)	360 (3)	3372 (29)	1813(15)
5	0.87(80)	0.61(61)	579(5)	583 (4)	4291 (39)	3135(24)
6	0.94(58)	0.69(38)	714(4)	524 (3)	3624 (22)	3333(16)
7	0.71(78)	0.81(72)	592(6)	505 (4)	3968 (42)	1830(16)
8	0.69(69)	0.81(70)	522(5)	452 (4)	3294 (32)	1703(15)
9	0.65(48)	0.58(36)	409(3)	310 (2)	4293 (32)	1137(7)
10	0.72(71)	0.88(58)	646(7)	536 (4)	4097 (42)	1412(10)
11	0.72(52)	0.59(36)	733(5)	457 (3)	5199 (38)	1995(12)
12	0.68(53)	0.59(33)	598(5)	411 (2)	3423 (29)	1584(9)
13	0.86(74)	0.66(46)	566(5)	460 (3)	3799 (32)	2083(14)
14	0.84(76)	0.87(71)	571(5)	561 (5)	4036 (36)	1683(14)
15	0.72(85)	0.61(40)	745(9)	447 (3)	4573 (54)	1093(7)
Mean	0.76(70)	0.70(50)	607(6)	466 (3)	4014 (37)	1862(13)
Harvest × genotype LSD		0.19		152.7		1209.1
d.f.		46		51		50
Harvest date LSD [a]		0.18		154.9		1222.9
d.f.		47		47		47

[a] For comparisons with the same harvest date.

However, following harvest new shoots can be killed by frost from which they were protected by the thatch effect of the dead biomass. Loss of new shoots may result in new growth not being vernalised and shoots remaining vegetative.

Perennial crops allow the build-up of insects in the foliage and some may damage the crop. RCG is one of the host plants of *A. ophiogramma* and therefore its presence in the crop is inevitable.[24] Different species of frit fly can emerge at different times, which can extend the period in which damage occurs and makes it more complicated to design control strategies.[25]

Yield

Low yield in the first year is to be expected as plants establish, and yield was much higher in subsequent years. Since genotypes were planted at the same density, initial growth differences from interplant competition were probably small until full crop cover was reached, but the greatest influence on the yield of genotypes is probably due to genetic diversity, which is well known in RCG.[2,26] The greater yield of several genotypes compared to the commercial variety shows the potential of improving yield through genotype selection and breeding. Adverse interaction with the environment may have been the reason why G3 and G4 failed to grow properly.[26]

Most studies that report dry matter production of RCG are for forage and conservation purposes and use management strategies that make comparison with our results inappropriate. However, our yields compare favourably with those for a January harvested crop on an organic soil in England[27] and for a range of ecotypes in Sweden,[10] and slightly better than a crop in Finland harvested either at seed maturity or at a delayed harvest in the following spring.[28] Yield was lower than for a range of switchgrass cultivars and *Miscanthus* × *giganteus*, evaluated as energy crops in adjacent experiments in the same field at Rothamsted.[29] Cumulative yields show only small differences between the best genotypes, although year-to-year ranking differs. In commercial terms, G1 would provide the best return for a conventional harvest but G8 for the delayed harvest. Our results do not identify a relationship between geographic origin of a genotype and yield.

Although this study was confined to four years of growth, the long-term productive potential of RCG has been demonstrated in Finland, where productivity was maintained for eight years.[28] Harvestable yield at the conventional time was greater than at the delayed harvest except in 1996 when the closeness of the two harvest dates could be the explanation for the result. The average loss of biomass in 1997 and 1998 was the same but individual genotypes differed greatly in the amount lost in both years. For example, G2 lost twice as much biomass in 1997 than in 1998, although the time between harvests was longer in 1998. In contrast, G15 lost three times as much biomass in 1998 than in 1997. It will be important to investigate the reason for this inconsistency because of the economic significance of selecting the right genotype.

Table 10. Chemical composition (weight, % dry matter) of RCG genotypes in 1998 compared to values for straw and wood chip published by Sander[29]

	Reed canary grass genotypes			
Element	Conventional harvest Range	Delayed harvest Range	Straw Range	Wood chip Range
N	0.65–0.94	0.59–0.87	0.3–1.5	0.1–0.7
P	0.05–0.07	0.03–0.05	0.03–0.2	0.02–<0.1
K	0.3–0.4	0.1–0.3	0.2–1.9	0.05–0.4

Delaying harvest to reduce mineral concentration was not particularly successful for N or P but K concentration was reduced on average by 54%, probably as a result of the leachability of K from biomass.[30] The inconsistencies in the changes in mineral concentration cannot be explained satisfactorily but could be a result of several factors. The harvesting method used required cut biomass to be collected from the soil surface and this could result in soil contamination, giving an elevated mineral concentration on analysis. Variability in stem maturation as a result of different flowering dates could later affect the remobilisation of minerals to roots and rhizomes. Maturation could also be affected by the 'thatch effect', providing a protective environment for short stems and new shoots. Mineral composition is an important characteristic of biomass intended for combustion. While different combustion technologies have different fuel specifications, the overall objective is to have fuel with the lowest possible mineral content at harvest to maximise combustion efficiency and minimise gas emissions. Our results compare favourably with those for straw and wood chip, which are both used for fuels for combustion (Table 10). An additional benefit of low mineral content is lower compensatory applications of fertilizer to replace mineral offtake at harvest. Offtake of P and K was small compared to the input of annual fertilizer (Tables 2 and 9). Therefore, at the level of yield obtained, inputs of P and K could be reduced and application need not be every year, thereby making further savings in cost. Delaying harvest improved quality but there was a substantial loss of biomass. It remains to be seen if a power generator would be prepared to pay more for the improved product in order to give the grower the same return as from the unimproved biomass.

CONCLUSIONS

The experiment has shown that RCG has potential as a biofuel. Many genotypes produced more biomass than a commercial variety used as a benchmark. Delaying harvest improved biomass quality by reducing moisture and mineral content in most genotypes, but there was a substantial loss of biomass. Biomass quality is suitable for use in a modern combustion plant but it remains to be determined if an end user of biomass with improved quality would pay a premium to give the grower the same or better return as from unimproved biomass. Growers may not be able to capitalise on yield potential until pest infestations are better understood and managed. Genetic variability within the species offers great potential to improve yield and quality through selection and breeding.

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