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Switchgrass (*Panicum virgatum* L.) as an alternative energy crop in Europe
Initiation of a productivity network

Final Report for the period from 01-04-1998 to 30-09-2001

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1 Executive summary and main conclusions

There is an increasing interest in Europe in biomass crops as a source for renewable CO_2-neutral energy and as a fibre source for the production of paper and other renewable materials. Many different plants are being considered for this purpose. For example trees such as willow, eucalyptus and poplar and annual crops such as hemp.
Switchgrass is a perennial C_4 grass propagated by seed that can be established at low cost and risc and requires very low inpots while giving high biomass yields even on marginal soils.

Switchgrass (*Panicum virgatum* L.) is one of the perennial rhizomatous grasses being developed for the purpose of biomass production. Other perennial rhizomatous grasses being developed in Europe include *Miscanthus*, reed canary grass (*Phalaris arundinacea*), and giant reed (*Arundo Donax*).

Switchgrass is a native of North American where it occurs naturally from 55º N latitude to deep into Mexico, mostly as a prairie grass. In North America it has long been used for soil conservation and as a fodder crop. Both in America and Europe it can be found as an ornamental plant. The grass is also found in South America and Africa where it is used as a forage crop.

Since the early 1990s the crop has been developed as a model herbaceous energy crop for ethanol and electricity production in the USA and in Canada and it is also being considered as a paper pulp production feedstock.

In this project switchgrass is being investigated as a novel lignocellulosic C_4 biomass crop for adaptation to European conditions and the use for both energy and fibre applications. Information from literature, from small experiments conducted in Europe, and results from ongoing research on other perennial rhizomatous grasses serve as a starting point for the project.

In the spring and summer of 1998 field experiments have been started at 4 sites in northern Europe (Wageningen and de Noordoostpolder in The Netherlands, Braunschweig in Germany and Rothamsted in The United Kingdom) and 2 sites in southern Europe (Aliartos in Greece and Trisaia in Italy) to evaluate switchgrass as a biomass crop for Europe.

The GENERAL OBJECTIVE of this project was to evaluate switchgrass as a promising cost effective energy crop that will add to agricultural diversification in Europe and to generate sufficient data to be able to initiate large scale production trials and facilitate further development of switchgrass in Europe.

These objectives were translated into the following specific objectives:

1. Identification of existing varieties and germplasms that are adapted to specific geographical regions of Europe.
2. Determination of potential dry matter production of switchgrass in small production plots.
3. Determination of nitrogen fertiliser requirement of switchgrass.
4. Collection of physiological data on switchgrass to explain biomass production and quality.
5. Identification of best seed establishment methods for European conditions.
6. Evaluation of winter hardiness of switchgrass under European conditions.
7. Development of a pilot model for switchgrass biomass production.
8. Determination of suitability of switchgrass for various thermal conversion processes (pyrolysis, gasification and combustion).
9. Evaluation of switchgrass fibre quality
10. Evaluation of economic and environmental aspects of the use of switchgrass as an energy crop and as a fibre crop or a combined energy / fibre crop.
11. Comparison of switchgrass to other energy and fibre crops.

Are there existing varieties and germplasms that are adapted to specific geographical regions of Europe?

It is possible to find switchgrass varieties that are adapted to most regions of Europe. The latitude of origin of a variety is the most important aspect determining the area of adaptation of a variety. Generally the use of varieties originating at southern latitudes can increase DM yields but it will also increase the chance of establishment failures in the first year and a decline in yields over time. Furthermore the quality of the biomass will be reduced (high moisture and nutrient content) if the variety does not mature in the fall. The best variety for a given latitude or geographical area will be a compromise between yield, quality and winter survival. From the current data on switchgrass grown in Europe it appears that switchgrass may be grown further north than in North America.
Specific recommendations for using varieties are given in Chapter 10.

What is the potential dry matter production of switchgrass in small production plots?

In the current project yields of up to 18 tonnes dry matter/ha were found in NW Europe and up to 25 tonnes dry matter/ha were found in Southern Europe. Under proctical conditions these yields should be lower. Accurate estimates will have to be obtained on large filed experiments over longer periods of time since switchgrass is a perennial grass which takes years to

What is the nitrogen fertiliser requirement of switchgrass

Nitrogen fertiliser requirements were generally found to be low as the crop failed to show yield response to fertiliser applications at 4 out of 5 experimental sites. The current research shows that between 0 to 50 kg N/ha/year is adequate for NW European sites while at higher productive sites in southern Europe 50 to 100 kg N/ha/year should be adequate. More specific recommendations for quantity of nutrients cannot be made because it will depend on the fertility status of the site.

What determines the yield and biomass quality of switchgrass?

Yield and quality of switchgrass are determined by a range of factor of which the origin of the variety is probably the most important. (see discussion in Chapter 5).

Which seed establishment methods for European conditions are recommended?

Seed establishment makes switchgrass a very attractive biomass crop since it is inexpensive and reduces financial risks. Experiments have shown that no-till establishment methods are suitable for switchgrass, (See Chapter 6 for details). Further development of methods for specific regions is possible to decrease establishment risk and cost.

Conclusions

Switchgrass can be grown in Europe and it can be used to produce inexpensive biomass under low input conditions and at a very low environmental impact.

Switchgrass biomass can de used for thermal conversion to electricity and heat and also has potential to be a fibre source for paper pulp production where it can replace hardwood or as a feedstock for lignocellulose to ethanol production. Other promising applicatiosn of switchgrass fibre include as re-inforcing and filling agent in thermoplastic materials.

It is necessary to gain experience with switchgrass under large field conditions and over a longer period of time to assess yield stability and other factors.

2 Switchgrass in NW Europe[1]

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2.1 Introduction

Switchgrass (*Panicum virgatum* L.) is a perennial C_4 grass native to North America where it occurs naturally from 55º N latitude to deep into Mexico, mostly as a prairie grass. In North America it has long been used for soil conservation and as a fodder crop and it is also used world-wide as an ornamental plant. The grass is also found in South America and Africa where it is used as a forage crop. Since the early 1990s the crop has been developed as a model herbaceous energy crop for ethanol and electricity production in the USA and Canada. Since 1998 switchgrass is being investigated as a novel lignocellulosic C_4 biomass crop for adaptation to European conditions. It is propagated by seed, which contributes to low cultivation costs.

This chapter will concentrate on the field experiments performed at sites in the UK, Germany and the Netherlands that have similar climatic conditions as defined by the amount of rainfall, temperature, day-length, etc. Therefore the same varieties can be compared between different sites.

The main objective of the research presented here was to evaluate the adaptation of switchgrass varieties to NW European conditions under different soil conditions and nitrogen stages.

2.2 Methods and Materials

Site and treatments

In 1998, two types of trials were established at two sites in The Netherlands and at one site in The UK and Germany each. The first, nursery, trial aims to compare a wide variety of switchgrass varieties on small plots, no further treatments are applied. The other trial aims to compare performance of 5 switchgrass varieties under two or three nitrogen stages (0, 75 and 150 kg N/ha) on larger plots. The experimental conditions and experimental layout are presented in Table 1.

Measurements

During three growing periods (1998, 1999 and 2000), a series of measurements were carried out to assess establishment and performance of the different varieties.

At regular intervals observations were made to assess the conditions of the plots. Visual observations were made for stand or establishment rating, disease rating, lodging, maturity, blooming, weed cover, etc. Stand ratings were scored from 0 to 6: no emergence (0), few plants visible (1), One row visible (2), several rows visible but with gaps in the row (3), rows clearly defined but may have gaps (4), no gaps (5), or excellent stand (6).

At the end of each growing season the final harvest took place after a killing frost in winter when aboveground biomass had died and was drying down. The fresh and dry matter yields were determined. Nutrient analysis of the biomass is discussed in Chapter 4.

1 This chapter is to be submitted for publication.

Table 1. Conditions and set-up of the two experiments.

	The Netherlands		UK		Germany	
Experiment:	Productivity	Nursery	Productivity	Nursery	Productivity	Nursery
Site	Wageningen	N.O. Polder	Rothamsted		Braunschweig	
Latitude	51°58´	52°38´	51°48´		52°18´	
T January °C	1,8	1,4	3,1		0,4	
T July °C	16,6	17,4	15,9		17,1	
Prescipitation, mm	700	747	688		619	
Soil texture	Coarse	Fine	Moderately fine over fine		Moderately coarse over coarse	
pH	5,2	7,5	7		6,5	
Experimental layout	Randomised complete block design in three blocks				Split plot design in three blocks, with variety as main plot and N treatment as a split	Randomised complete block design in three blocks
Treatments	0 and 75 kg N/ha and 5 switchgrass varieties	13 switchgrass varieties	0 and 75 kg N/ha and 5 switchgrass varieties	15 switchgrass varieties	0, 75 and 150 kg N/ha and 5 switchgrass varieties	15 switchgrass varieties
Plot size	8 x 6 m	4 x 3.5 m	8 x 5 m	4.5 x 2 m	7.5 x 6.5 m	3.8 x 3.6
Row distance	15 cm		14.2 cm		15 cm	
Seeding date	2 June	28 May	22 June		23 June	22 June
Weed control	Chemical, manual, mowing	Chemical, mowing	Chemical		Chemical, manual	

Table 2. List of switchgrass varieties used in the six experiments in NW Europe (detailed descriptions of the switchgrass varieties are presented in Chapter 5).

The Netherlands		UK		Germany	
Productivity	Nursery				
Noordoost-Polder	Wageningen	Rothamsted		Braunschweig	
Blackwell	Blackwell	Blackwell	Alamo	Blackwell	Blackwell
Carthage	Caddo	Carthage	Blackwell	Carthage	Caddo
Cave-in-Rock	Carthage	Cave-in-Rock	Caddo	Cave-in-Rock	Carthage
Forestburg	Cave-in-Rock	Pangburn	Cave-in-Rock	Forestburg	Cave-in-Rock
Summer	Forestburg	Summer	Forestburg	Summer	Kanlow
	Kanlow		Kanlow		Nebraska-28
	NL 93-1		Nebraska-28		NL 93-1
	NL 93-2		NL 93-1		NL 93-2
	NU 94-2		NL 93-2		NU 94-2
	Pangburn		NU 94-2		Pangburn
	REAP 921		REAP 921		REAP 921
	Shelter		Shelter		Shelter
	Summer		SU 94-1		SU 94-1
			9005439		Sunburst
			9005438		Trailblazer

[1] CIR = Cave-in-Rock. For more details on varieties see Chapter 5 and Annex.

2.3 Results

A selection of the results of field measurements are presented in Table 3 to 9 for the six experimental sites in The Netherlands, UK and Germany.

Stand ratings

A general visual observation of the stand over three years is presented in Table 3 and 4. We see that in the first year (summer 1998) all varieties had good stand scores except for those that had low emergence due to low seed germination (REAP 921).

At the start of the second year stand scores were lower than in the previous year. In The Netherlands and the UK the lowest scores were recorded for southern varieties like Carthage and Pangburn in the yield trials and for Pangburn, NL 93-1, NL 93-2, Alamo and Kanlow. In Germany stand scores were low for most of the varieties except for northern varieties like Cave-in-Rock, Summer, Shelter, Nebrasca-28, Sunburst. In the Netherlands and especially in the UK most southern varieties like Carthage, Pangburn, Kanlow and even Alamo recuperated later in the season or in the next year to obtain reasonable to good stand ratings. Only NL93-1 failed completely in The Netherlands. In Germany southern varieties like Kanlow, NL93-1, NL93-2, Pangburn, SU 94-1 did not recuperate much and some failed completely. This result should be explained by the colder climatic conditions in Germany compared to The Netherlands and the UK (see Table 1) which resulted in more winter damage for southern varieties leading to almost complete stand loss.

In the first year weeds were a major concern. Chemical and mechanical (mowing above switchgrass height) control was effective. Weeds were also a problem at the start of the second year especially in varieties that emerged late. This aspect of establishment is also discussed in Chapter 6 and 10.

Visual disease ratings were recorded throughout the experiments. Some fungal diseases were observed. For example eyespot was found on stem bases of a few plants during the summer, most prevalent on Blackwell. The disease levels were low, generally less than 1 on a scale from 0 to 6, and should not lead to yield losses.

Table 3. Yield trial. Switchgrass relative stand rating in the first, second and third year after establishment at 3 sites in NW Europe (0 = extremely poor stand, 6 = excellent stand).

Site:	Noordoostpolder (NL)				Rothamsted (UK)				Braunschweig (D)			
Date:	1811-98	11-5-99	22-9-99	4-08-00	23-09-98	22-6-99	5-10-99	13-7-00	21-07-98	22-04-99	21-07-99	24-07-00
Treatment	Rating 1 to 6											
Blackwell	5.1	*3.8*	6.0	6.0	4.3	*4.0*	5.9	5.7	4.7	*3*	3	4
Carthage	5.3	*3.0*	6.0	6.0	4.3	*5.2*	5.8	5.7	5.0	*1.7*	3	4
Cave-in-Rock	5.6	*4.6*	6.0	6.0	4.3	*3.0*	5.7	5.2	6.0	*4.1*	5	5
Forestburg	3.5	*3.3*	5.5	6.0	-	-	-	-	4.0	*3.9*	6	5
Pangburn		-	-		4.3	*1.0*	3.8	4.2	-	--	--	
Summer	4.5	*3.7*	6.0	6.0	4.2	*4.7*	6.0	5.9	4.0	*3.9*	4.5	5
0 N	-	*3.8*	5.8	6.0	-	*3.7*	5.4	5.3	-	-	-	-
75 N	-	*3.6*	6.0	6.0	-	*3.4*	5.5	5.3	-	-	-	-

Table 4. Nursery trial. Switchgrass relative stand rating in the first, second and third year after establishment at 3 sites in NW Europe (0 = extremely poor stand, 6 = excellent stand).

Site:	Wageningen (NL)				Rothamsted (UK)				Braunschweig (D)			
Date:	17-11-98	*6-5-99*	7-10-99	2-08-00	23-09-98	*13-5-99*	5-10-99	13-07-00	29-07-98	22-04-99	27-08-99	8-9-00
Variety ?	Rating 1 to 6											
Alamo	-	-	-	-	4.3	*0.3*	3.7	3.3	-	-	-	-
Blackwell	5.3	*4.8*	6.0	5.3	5.0	*5.3*	6.0	5.0	4.3	*3*	3	3
Caddo	5.7	*4.3*	6.0	5.7	5.0	*5.0*	6.0	5.0	5.3	*1*	1	3
Carthage	5.3	*4.5*	6.0	5.8	-	-	-	-	4.3	*2*	3	4
Cave-in-Rock	5.8	*6.0*	6.0	6.0	5.0	*5.3*	6.0	5.7	5.0	*4*	6	6
Forestburg	4.2	*4.3*	5.4	5.2	4.3	*4.3*	5.7	5.3	-	-	-	-
Kanlow	5.0	*3.0*	5.4	6.0	4.0	*1.3*	4.7	4.3	4.0	*1*	0	1
Nebraska-28	-	-	-	-	4.7	*5.7*	6.0	5.0	6.0	*5*	6	5
NL 93-1	4.3	*1.3*	2.3	1.7	4.0	*0.7*	2.0	3.0	4.0	*1*	0	0
NL 93-2	5.3	*3.5*	4.8	5.3	4.7	*1.3*	4.3	4.3	4.0	*1*	0	1
NU 94-2	5.0	*4.7*	6.0	6.0	4.3	*4.3*	6.0	5.7	4.0	*1*	2	4
Pangburn	4.8	*2.0*	4.1	4.5	-	-	-	-	3.3	*1*	0	1
REAP 921	3.5	*3.7*	6.0	6.0	2.0	*3.7*	4.3	4.7	2.7	*1*	2	3
Shelter	5.7	*5.7*	6.0	6.0	4.3	*5.0*	6.0	5.3	5.3	*4*	4	5
SU 94-1	-	-	-	-	5.3	*5.3*	6.0	5.3	5.7	*1*	1	2
Summer	4.2	*3.8*	5.7	5.8	-	-	-	-	-	-	-	-
Sunburst	-	-	-	-	-	-	-	-	5.0	*5*	6	6
Trailblazer	-	-	-	-	-	-	-	-	6.0	*2*	1	2
9005439	-	-	-	-	4.0	*4.7*	6.0	5.0	-	-	-	-
9005438	-	-	-	-	4.0	*4.7*	6.0	5.0	-	-	-	-

Lodging

Lodging was observed at all sites in NW Europe. In the first year lodging was very mild and was only recorded in The Netherlands (Table 5). In the second year lodging was more pronounced especially in The Netherlands and the UK. There were differences in degree of lodging between varieties. Varieties like Blackwell and Carthage showed more lodging than varieties like Cave-in-Rock or Summer. In the second year (1999) most varieties recovered from lodging by the end of the season. Yield depressions due to lodging were probably minor.

In the third year lodging was very severe both in the Netherlands and the UK as illustrated by the high lodging scored presented in Table 5. In 2000 the plants did not recover and there probably was a negative effect on yield, and moisture and nutrient content of the biomass especially in The Netherlands. See discussion below and in Chapter 4. Some varieties lodged later than others, but in the end all showed severe lodging. More robust varieties like Pangburn and Summer showed less lodging but this was still very significant. 2000 appears to have been an exceptional year since in 2001 less lodging was observed. In 2000 other crops grown near to the experimental plots (wheat) showed unusual lodging indicating the conditions were unusually favourable to lodging that year.

Generally there was no difference observed between different nitrogen treatments with respect to lodging. When differences were apparent at the start of lodging these were not consistent between The Netherlands and The UK

Table 5. Yield trial. Switchgrass lodging ratings (0= no lodging, 6= all plants lodged flat) at Noordoostpolder site in The Netherlands and Rothamsted (UK).

		Noordoospolder (NL)					Rothamsted (UK)	
Variety	N Trt	18-03-99*	22-09-99	20-06-00	10-11-00	18-11-01	21-7-00	20-9-00
		Lodging rating (1-6)						
Blackwell	0	3.1	1.3	1.3	5.7	5.3	4.7	4.5
	75		3.3	2.7	5.5	4.8	4.2	4.5
Carthage	0	4.6	0.2	0.2	5.0	5.3	0.0	3.8
	75		1.8	0.2	5.4	5.4	0.0	2.7
CIR	0	1.0	0.0	0.0	5.0	4.0	1.5	4.5
	75		1.5	0.0	4.8	5.0	1.8	4.0
	150		2.2	0.0	5.3	4.4	-	-
Forestburg	0	0.7	0.0	1.2	3.8	3.7	-	-
	75		0.3	2.8	5.3	3.8	-	-
Pangburn	0	-	-	-	-	-	0.0	2.0
	75	-	-	-	-	-	0.0	0.9
Summer	0	0.7	0.0	0.0	4.0	3.3	0.0	4.0
	75		0.5	0.0	4.2	3.5	0.0	3.5
Avg. switchgrass	0	3.3	0.3	0.5	4.7	4.3	1.2	3.7
	75		1.5	1.1	5.1	4.5	1.2	3.1

*In the first growing season no N stage was implemented yet.

Dry matter yield

Dry matter yield of the six experiments is presented in Table 6 and 7. Yields increased from less than 2 tonnes in the first years to up to 12 tonnes per ha in the second year and up to 18 tonnes in the third year. This shows that yield development of switchgrass takes time to develop. Further increases in average yield of most switchgrass varieties are likely. It is known that on clay soils yield takes longer to reach maximum potential. Carthage was among the two best yielding varieties in The Netherlands and The UK (Table 5) but it yielded the worst in Germany. At all sites the lowest yields were recorded for northern varieties that matured very early (Forestburg, 9005438, 9005439) or very late (Alamo, Kanlow, Pangburn, NL93-1). These southern late maturing varieties also had the lowest stand scores because of slow re-growth or stand failure. For further discussion on the relationship between latitude and yield and other attributes see Chapter 5. The highest yields were obtained in The UK (and in The Netherlands and Germany) with the latest maturing varieties that did not suffer from severe stand loss in (the first) winter.

Nitrogen response (Table 7) was not found at The Netherlands and the UK where both the 75 kg N/ha and control treatments had similar yields. There was a negative effect of N application at best. In contrast for the experiment in Germany increased N stage increased yield accordingly. In the third year average DM yield almost doubled from 4.3 to 8 tonnes as N application increased from 0 to 150 kg N/ha.

In the Netherlands *Miscanthus gigantheus* was also included in the experiments. Results show that yield were low compared to most switchgrass varieties but in the third year yields reached up to 14 tonnes at the sandy site in Wageningen and up to 50 tonnes at the Clay site in de Noordoostpolder. It is known that small plot yield estimates will overestimate yields.

Plants were more than 3 meters high in that year. The very high yields are probably not realistic and should not be extrapolated to larger fields. Light interception over the season determines to a large extent the yield of a crop. Especially with a high crop light is intercepted over a larger area than the basic plot size. This should account for the very high yield estimates. The same will apply to a lesser extent to the switchrass yield estimates as light from a larger area is intercepted than the sole plot.

Table 6. Nursery trial. Switchgrass dry matter yield (DM) at harvest after in winter after the first, second and third year.

Site:	Wageningen (NL)			Rothamsted (UK)			Braunschweig (D)		
Date:	17-03-99	12-01-00	6-03-01	26-01-99	20-12-99	16-01-01	19-01-99	22-11-99	19-01-01
Variety ?	tonne/ha								
Alamo	-	-	-	0.4	6.6	16.7	-	-	-
Blackwell	1.3	8.2	10.1	0.5	10.2	12.1	1.5	4.1	11,2
Caddo	1.2	8.1	10.2	0.8	10.1	12.1	2.2	2.6	7,8
Carthage	0.8	6.5	16.0	-	-	-	1.1	4.0	10,5
Cave-in-Rock	1.2	9.2	13.8	0.5	10.3	15.3	1.8	6.4	14,5
Forestburg	0.5	6.1	8.6	0.1	5.7	11.6	-	-	-
Kanlow	1.1	6.1	17.5	0.6	8.4	18.5	0.9	0.5	2,0
Nebraska-28	-	-	-	0.1	6.9	11.1	1.6	7.4	13,2
NL 93-1	0.8	2.0	7.3	1.0	4.6	9.0	0.7	0.1	0,3
NL 93-2	1.2	5.6	19.6	0.9	7.6	18.9	1.1	0.4	2,1
NU 94-2	1.1	8.2	15.2	0.2	9.1	15.1	1.3	3.8	12,2
Pangburn	0.9	4.3	12.6	-	-	-	0.7	0.5	2.0
REAP 921	0.3	4.5	11.5	----	5.9	12.0	0.6	2.7	8,8
Shelter	1.0	6.8	12.8	0.1	7.7	12.9	1.2	4.6	10,2
SU 94-1	-	-	-	1.5	12.4	14.2	1.9	1.7	5,3
Summer	0.9	6.2	12.4	-	-	-	-	-	-
Sunburst	-	-	-	-	-	-	1.3	7.2	13,8
Trailblazer	-	-	-	-	-	-	2.4	2.1	7,7
9005439	-	-	-	0.8	5.8	10.3	-	-	-
9005438	-	-	-	0.1	5.8	10.7	-	-	-
Miscanthus	–	2.9	14.0	-	-	-	-	-	-

Table 7. Yield trial. Switchgrass dry matter yield (DM) at harvest in winter after the first, second and third year.

Site:	Noordoostpolder (NL)			Rothamsted (UK)			Braunschweig (D)		
Date:	18-03-99	25-01-00	20-02-01	26-01-99	17-01-00	13-02-01	19-01-99	15-11-99	19-01-01
Treatment	tonne/ha								
Blackwell	0.5	5.3	8.8	0.9	9.2	13.6	1.6	2.1	6.4
Carthage	0.2	5.5	10.7	1.3	9.9	13.9	1.0	2.0	5.9
Cave-in-Rock	0.6	5.4	9.3	1.2	8.7	14.6	1.5	3.0	6.9
Forestburg	0.2	3.6	6.1	-	-	-	0.6	2.8	6.2
Pangburn	-	-	-	1.0	7.6	11.3	-	-	-
Summer	0.3	4.6	10.0	0.9	9.1	13.0	0.5	2.3	6.4
0 N	-	4.8	9.7	-	9.2	14.5	-	2.0	4.3
75 N	-	5.1	8.3	-	8.5	12.0	-	2.4	6.8
150 N	-	-	-	-	-	-	-	3.0	8.0
Miscanthus 0 N	-	1.0	40.6	-	-	-	-	-	-
Miscanthus 75 N	-	1.2	49.8	-	-	-	-	-	-

Moisture content

Moisture content is important for a biomass crop since it determines a.o. the cost of transport and possibilities of storage. The crop dries down in fall and winter until a low enough moisture content is reached which makes longer times storage possible. If the crops fails to dry down sufficiently before re-growth of the plants in spring biomass cannot be stored, at a moisture content above 20% biomass can only be stored for a short period, and will have to be dried or used immediately. Drying of biomass is expensive**.**

In Table 8 and 9 moisture contents of the biomass are presented at harvest in winter or early spring. In the first year later harvesting in the Netherlands resulted in very dry biomass compared to earlier harvesting in The UK and Germany. In the UK the highest moisture contents were consistently recorded for Alamo, NL93-1, Kanlow and Pangburn. These are robust southern varieties that matured later than the other varieties resulting in a lower rate of dry-down during fall and winter and higher moisture content at harvest. For the Netherlands the higher moisture content of late maturing varieties was not as clear which is probably due to lodging which prevented all varieties to dry down. In Germany the same effect as in The UK could be observed though the moisture content measurements from very poor stands should be less reliable.

Table 8. Nursery trial. Switchgrass moisture content at harvest in winter after the first, second and third year.

Site:	--- Wageningen (NL) ---			--- Rothamsted (UK) ---			--- Braunschweig (D) ---		
Date:	17-03-99	12-01-00	6-03-01	26-01-99	20-12-99	16-01-01	19-01-99	22-11-99	19-01-01
Variety ?	--- Moisture % ---								
Alamo	-	-	-	63	59	43	-	-	-
Blackwell	12	23	32	50	32	26	25	49	-
Caddo	8	20	21	46	33	26	25	46	-
Carthage	7	16	32	-	-	-	27	45	-
Cave-in-Rock	7	17	27	54	37	22	25	45	-
Forestburg	9	20	20	40	26	21	-	-	-
Kanlow	8	24	31	69	46	38	27	56	-
Nebraska-28	-	-	-	37	29	31	25	41	-
NL 93-1	18	21	32	57	51	40	28	49	-
NL 93-2	8	26	33	68	50	30	27	62	-
NU 94-2	7	18	25	54	39	24	29	53	-
Pangburn	8	24	28	-	-	-	30	56	-
REAP 921	19	18	29	–	29	22	29	47	-
Shelter	8	22	25	41	27	23	27	50	-
SU 94-1	-	-	-	47	38	24	23	56	-
Summer	15	19	25	-	-	-	-	-	-
Sunburst	-	-	-	-	-	-	24	48	-
Trailblazer	-	-	-	-	-	-	24	51	-
9005439	-	-	-	35	25	24	-	-	-
9005438	-	-	-	46	29	22	-	-	-
Miscanthus	----	26	33	-	-	-	-	-	-

Table 9. Yield trial. Switchgrass biomass moisture content at harvest in winter after the first, second and third year at three sites in NW Europe.

Site:	Noordoostpolder (NL)			Rothamsted (UK)			Braunschweig (D)		
Date:	18-03-99	25-01-00	20-02-01	26-01-99	26-01-00	-01-01	19-01-99	15-11-99	19-01-01
Treatment	Moisture %								
Blackwell	12	24	65	54	31	26	37	44	24
Carthage	12	27	67	56	35	26	44	44	25
Cave-in-Rock	12	29	68	54	32	27	38	44	24
Forestburg	15	20	62	-	-	-	30	35	22
Pangburn	-	-	-	67	40	30	-	-	-
Summer	13	21	60	48	26	20	24	32	22
0 N	-	23	63	-	32	26	-	39	23
75 N	-	25	65	-	33	25	-	40	23
150 N	-	-		-	-	-	-	41	23
Miscanthus 0 N	-	35	27	-	-	-	-	-	-
Miscanthus 75 N	-	44	26	-	-	-	-	-	-

2.4 Conclusions

Yields of up to 18 tonnes dry matter per ha were recorded for winter harvested switchgrass.

The highest yields were obtained in The UK) with the latest maturing varieties that did not suffer from severe stand loss in (the first) winter. The same was the case for The Netherlands and Germany.

For switchgrass yield development to reach maximum potential probably takes more than 3 years.

Nitrogen response was absent at 2 out of 3 experimental sites.

In the first year weed was the most important concern. In following years lodging was the moist important concern. Lodging of switchgrass was recorded to different degrees at all sites in NW Europe. Varieties differ in the degree of susceptibility to lodging if the conditions are relatively mild.

3 Switchgrass in the Mediterranean region[2]

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3.1 Introduction

Switchgrass (*Panicum virgatum* L.) is an erect warm-season (C4) perennial grass where it occurs naturally from 55°N latitude to deep into Mexico, mostly as a prairie grass. Over the last two decades it has become an important warm-season pasture grass for fodder production when cool season C3 grasses are less productive in summer (Moser and Vogel, 1995). Many reasons are given for using switchgrass as a biomass crop for energy and fibre production. These include the high net energy production per ha,low production costs, low nutrient requirements, low ash content, high water use efficiency, large range of geographic adaptation, ease of establishment by seed, adaptation to marginal soils, and potential for carbon storage in soil (Christian and Elbersen, 1998; Saderson et al. 1996; Samson and Omielan, 1992).

Two ecotypes are generally defined based on morphological characteristics and habitat preferences. Lowland types are generally found in floodplains, they are taller, coarser, have a more bunch type growth habit, and may be more rapid growing than upland types (Moser and Vogel, 1996; Porter, 1996). Upland types are found in drier upland sites, they are finer stemmed, broad based, and often semi-decumbent. It is suggest that lowland types may be better suited as biomass fuel plants (Hultquist et al. 1996).
In Europe the research for switchgrass as a biomass crop for energy and fibre has started in 1998 in the framework of a European network (FAIR 5 CT97 3701). In the view of this work, experimental fields of switchgrass have been established in five European countries, two in the south (Greece and Italy) and three in the north (Germany, Netherlands and UK). Before that some research work on switchgrass had been conducted in UK and Germany (Christian and Elbersen, 1998; Lewandowski et al. 1998). It is estimated that in Europe some of 4 ha of experimental switchgrass fields exist of which 2.5 ha is within the current European Union sponsored switchgrass productivity network (Elbersen et al. 2001).
The main purpose of this work was to test the adaptability and biomass productivity of several switchgrass varieties in the Mediterranean region (Greece and Italy) as well as to test the productivity of five switchgrass varieties under three nitrogen fertilisations rates.

3.2 Methods and Materials

Site and treatments

In 1998, four switchgrass trials were established, two in Greece (Aliartos) and two in Italy (Trisaia). In each country a nursery and a productivity trial were established. The experimental layout in the nursery trial was a randomised complete block design in three replications, while in the productivity trial was a 5x3 factorial complete block design in three replications. A detailed description of all trials (site co-ordinates, treatments, experimental layout, plot size and sowing dates) is presented in Table 1.
Irrigation in both sites was necessary in order to ensure the good establishment of the crop as well as the high biomass yields. In both sites (Aliartos, Trisaia) the climate could be characterised as dry with 400mm/year mean precipitation. In both sites the soil type is SL with relatively low organic matter.

2 This chapter is to be submitted for publication.

Table 1. Description of the switchgrass trials in Greece and Italy.

	Nursery Trials		Productivity Trials	
	Greece (Aliartos)	Italy (Trisaia)	Greece (Aliartos)	Italy (Trisaia)
Sites coordinates	latitude 38^0 22, longitude 23^0 10 altitude 114 m	latitude 40^0 09, longitude 16^0 38 altitude 30 m	latitude 38^0 22, longitude 23^0 10 altitude 114 m	latitude 40^0 09, longitude 16^0 38 altitude 30 m
Treatments	*10 varieties* Caddo Cathage Cave-in-rock Forestburg Kanlow SL 93-2 SL 93-3 SL 94-1 SU 94-1 Summer	*15 varieties* Caddo Cathage Cave-in-rock Kanlow NU 94-2 Pangburn SL 93-2 SL 93-3 SL 94-1 SU 94-1 Summer Sunburst Trailblazer 9005439 9005438	*5 varieties* Alamo Blackwell Cave-in-Rock Kanlow Pangburn *3 nitrogen rates* N_1=0 kg N/ha N_2=75 kg N/ha N_3= 150 kg N/ha	*5 varieties* Alamo Blackwell Cave-in-Rock Forestburg Kanlow *3 nitrogen rates* N_1=0 kg N/ha N_2=75 kg N/ha N_3= 150 kg N/ha
Experimental layout	Randomised complete block design in three blocks		5x3 factorial complete block design in three blocks	
Plot size	3m x 4m	5m x 2.7m	6.5m x 7.5m	6.3m x 7.5m
Sowing date	3/6/98	17/7/98	31/5/98	16/7/98

3.3 Measurements

During all growing periods (1998, 1999 and 2000), in both sites, a series of measurements were carried out including canopy height, number of tillers per square meter and number of tillers per plant. In order to measure the number of tillers per square meter and number of tillers/plant a marked area sized 0.5 x 0.5 m^2 in each plot was used. At the end of each growing season the final harvest took place after a killing frost in order to determine the fresh and dry matter yields and yields components. The harvested area per plot was 4 m^2 in the productivity trial and 2 m^2 in the nursery trial and from the harvested material a quantity of 500 gr was taken and separated into stem and leaves. After the separation the samples from stems and leaves were oven-dried until constant weight for dry matter determinations.

3.4 Results

Nursery Trials

Plant height

Due to earlier sowing in the Greek trial all varieties had the opportunity to develop higher stems compared to the Italian trial (142.6 cm versus to 91.5 cm – mean values). In the second growing season the plant height was increased in both sites (30% in Greece and 64.4% in Italy). In the third year the plant height continued to increase only in the case of Italy (15.15%), while in Greece was decreased (14.24%). As it is presented in Tables 2 & 3 the mean plant height was higher in Greece in the first and the second growing season but in the third growing season this trend was changed.

At the end of the third growing season the plant height in Aliartos ranged from 153.3cm (Cathage, CIR and SU 94-1) to 173.3 cm (SL 93-3). In Trisaia the corresponding values ranged from 140 (Caddo) to 210 cm (SL 93-2, SL 93-3 and SL 94-1). It should be mentioned that the range among the tested varieties was larger in Italy (Tables 2, 3).

Number of tillers per square meter and tillers/plant

In both sites the number of tillers per square meter and tillers/plant was increased from the establishment to the second growing season but in the third year the increase was continued only in the case of the Italian trial (Tables 2 and 3). Thus, at the end of the third growing season the number of tillers per square meter and tillers/plant was higher in Trisaia. In more detail, the number of tillers per square meter in Trisaia was fluctuated from 1034 (Sunburst) to 2868 (Summer), while the corresponding data in Greece ranged from 1052 (Kanlow) to 2075 (CIR). Regarding the number of tillers/plant (2000) in Trisaia varied from 18.1 (NU 94-2) to 59 (9005439) and in Aliartos ranged from 19.2 (SL 93-2) to 30.3 (SU 94-1).

Yields

In both sites the dry matter yields for all varieties increased from the establishment to the second growing season. The increase in Greece was came up to 53.98%, while in Italy was 225.96%. Between the second and the third growing season the dry matter yields were continued to increase in Trisaia (73.11%), while in Aliartos the dry matter yields averaged overall varieties were almost the same.

Table 2. Growth characteristics (plant height, number of tillers/m², number of tillers/plant) and dry matter yields (t/ha) in Aliartos, Greece (1998, 1999 & 2000).

Varieties	Final canopy height (cm)			Number of tillers/m²			Number of tiller/plant			Dry matter yields (t/ha)		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Caddo	153.3	187.7	166.7	1174	1402	1107	9.2	27.5	21.7	10.7	20.1	20.1
Cathage	155.0	190.0	153.3	1190	1761	1613	9.6	25.7	23.5	15.2	18.9	17.5
CIR	146.3	186.7	153.3	1067	1920	2075	9.1	23.5	25.4	11.8	15.8	17.9
Forestburg	143.3	190.0	156.7	1056	1132	1337	9.8	20.0	23.6	13.2	19.0	18.4
Kanlow	133.3	180.0	160.0	832	1145	1052	10.0	25.6	23.5	10.4	17.1	21.3
SL 93-2	140.0	180.0	156.7	1070	1700	1229	9.4	26.5	19.1	11.6	16.8	16.7
SL 93-3	143.3	186.7	150.0	1090	1936	1428	10.1	30.3	22.3	12.4	19.0	17.8
SL 94-1	138.3	190.0	173.3	1070	1104	1153	9.2	21.6	22.6	9.4	15.8	18.8
SU 94-1	130.0	180.0	153.3	1032	1434	1544	8.1	28.1	30.3	8.5	14.0	11.3
Summer	143.3	183.3	166.7	989	1028	1053	8.7	24.2	24.8	12.1	21.1	19.3
Mean	142.6	185.4	159.0	1057	1456	1359	9.3	25.3	23.6	11.53	17.76	17.91

Table 3. Growth characteristics (plant height, number of tillers/m², number of tillers/plant) and dry matter yields (t/ha) in Trisaia, Italy (1998, 1999 & 2000).

Varieties	Final canopy height (cm)			Number of tillers/m²			Number of tiller/plant			Dry matter yields (t/ha)		
	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Caddo	90	140	140	-	1047	2068	-	16.9	33.3	2.31	7.59	10.10
Cathage	80	163	180	-	1020	1134	-	19.6	21.8	2.51	7.60	9.42
CIR	100	143	160	-	960	2268	-	18.5	43.6	2.53	7.11	11.37
Kanlow	100	133	190	-	1141	1067	-	25.9	24.2	1.36	4.71	15.30
NU 94-2	90	190	150	-	1080	1467	-	13.3	18.1	2.98	8.33	10.83
Pangburn	110	217	200	-	600	1668	-	14.6	40.7	2.42	8.50	11.91
SL 93-2	100	200	210	-	1080	1367	-	27.7	35.0	2.03	8.50	20.16
SL 93-3	100	107	210	-	747	1401	-	16.2	30.4	2.05	14.62	26.08
SL 94-1	100	117	210	-	867	1301	-	16.4	24.5	2.38	9.96	14.90
SU 94-1	90	130	160	-	627	2868	-	7.4	33.7	2.99	10.35	15.76
Summer	75	147	150	-	900	1234	-	16.1	22.0	1.31	6.28	7.79
Sunburst	75	147	160	-	540	1034	-	10.6	20.2	0.87	3.45	8.20
Trailblazer	80	143	170	-	1261	2468	-	24.7	48.3	2.84	5.78	10.67
9005439	-	133	150	-	1167	1534	-	44.8	59.0	-	1.71	5.63
9005438	-	147	160	-	1141	1134	-	24.2	27.0	-	2.59	7.28
Mean	91.5	150.5	173.3	-	945	1601	-	16.1	32.1	2.19	7.14	12.36

As it is shown in Figures 1 and 2 the range among the tested varieties in terms of dry matter yields in all years was quite large in Italian trial. More specifically, at the establishment year the dry matter yields in Italy ranged from 0.87 t/ha (Sunburst) to 2.99 t/ha (SU 94-1), while in the following year ranged from 1.71 t/ha (9005439) to 14.62 t/ha (SL 93-3) and in 2000 varied from 5.63 t/ha (9005439) to 26.08 t/ha (SL 93-3). It should be noted that in 1999 and 2000 the same varieties gave the highest and the lowest dry matter yields.

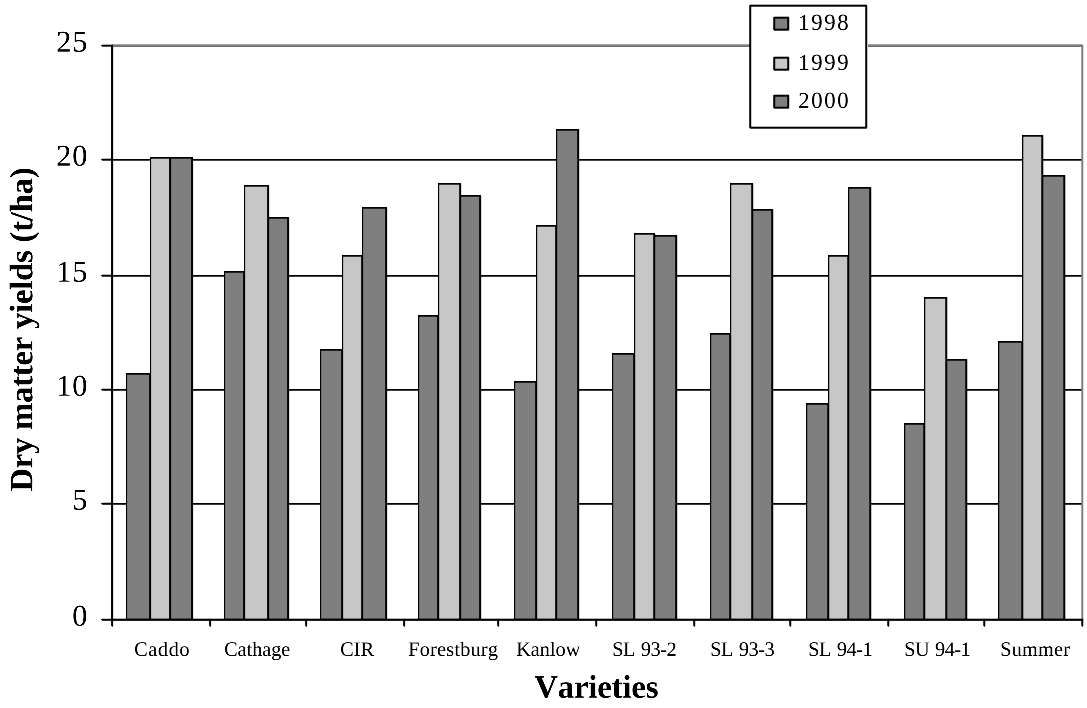

Figure 1. Dry matter yields (t/ha) for the tested varieties in Greece (1998, 1999 and 2000).

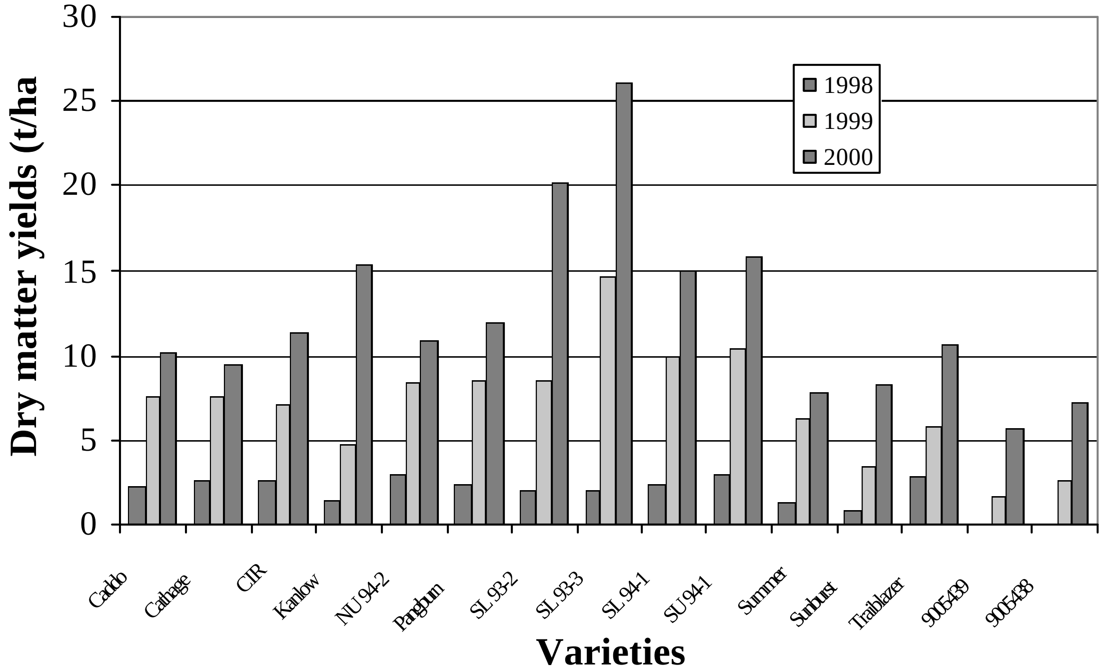

Figure 2. Dry matter yields (t/ha) for the tested varieties in Italy (1998, 1999 and 2000).

Productivity Trials

Plant height

At the end of each growing seasons the canopy height in the Italian productivity trial varied from 50 cm (Forestburg N_2 and N_3) to 105 cm (Alamo N_1 and N_2), 103 cm (Forestburg N_3) to 187 cm (Alamo N_3, Kanlow N_2 and N_3) and from 110 cm (Forestburg N_3) to 200 (Alamo N_2 and Kanlow N_2) in the first, second and third years, respectively. The corresponding values in the Greek trial ranged from 142 cm (CIR) to 179 cm

(Kanlow), 157 cm (CIR N_1) to 210 cm (Kanlow N_3) and 143 cm (Blackwell N_1) to 213 cm. (Pangburn N_3) in the first, second and the third years, respectively.

In the first year the plant height in the Greek trial was higher as compared to the Italian trial. This was due to the earlier sowing in Greece that all varieties had the opportunity to develop the stems higher as compared to the Italian trial where the sowing was delayed for about two months. However, in the second year the plant height increased in both sites (87% in Italy and 228% in Greece). But in the third year it continued to increase in Italy (11%), while in Greece it was decreased to 5%. However, the mean height in Greece was always a little higher (168 cm) than in Italy (163 cm). It is worth mentioning here that the height of switchgrass plants tends to get stabilized from the third year of its cultivation.

Number of tillers per square meter and tillers per plant

In both sites and all the treatments, the number of tillers per square meter and tillers per plant was increased from the establishment to the second growing season. However, in the third year the increase continued in most of the treatments in case of the Italian trial. At the end of the third growing season the number of tillers per square meter in Italy ranged from 734 (CIR N_2) to 1901 (CIR N_1), while the corresponding data in Greece fluctuated from 780 (Pangburn N_1) to 2534 (Blackwell N_3). Regarding the number of tillers per plant (in the year 2000), the mean value in Greece trial was higher (17) as compared to the Italian Trial (15).

Yields

The dry matter yields in both sites for all the tested varieties increased from the establishment to the second growing season. The average increase in Italy was come up to 224%, while in Greece it was 121%. In the third growing season the dry matter yields continued to increase in Italy (28%), while in Greece it was decreased to 22% averaged overall varieties. The percentage increase in dry matter yield in Italy was 8 times more from the first to the second year than from the second to the third year of the trial. Moreover, the range among the tested varieties in terms of dry matter yields in each year was comparatively large in the Italian trial, as is shown in Table 5. In the establishment year it ranged from 0.64 t/ha (Forestburg N_1) to 5.33 t/ha (Alamo N_3), in the second year from 4.09 t/ha (Forestburg N_3) to 16.11 t/ha (Alamo N_2), while in the third year from 6.36 t/ha (Forestburg N_1) to 18.67 t/ha (Alamo N_2) (Figure 3). It should be noted that in all the growing years the same varieties gave the lowest and the highest dry matter yields.

In the Greek trial the range of the dry matter yields among the tested varieties was comparatively less (Table 4). In the first year it ranged from 6.8t/ha (CIR) to 12.3 t/ha (Alamo), in the second year from 11 t/ha (CIR N_1) to 25 t/ha (Pangburn N_3), while in the third year from 11.4 t/ha (CIR N_1) to 18.1 t/ha (Pangburn N_3) (Figure 4). The most productive variety in the third growing season was the genotype Alamo in Italy and Pangburn in Greece. As regards the less productive one among the tested varieties, it was Forestburg (6.6 t/ha) in Italy and Kanlow (14.3 t/ha) in Greece.

Table 4: Growth characteristics (plant height, number of tillers/m2, number of tillers per plant) and dry matter yields (t/ha) in Greece (Greece) in 1998, 1999 and 2000.

Varieties	Final canopy height (cm)			Number of tillers/m^2			Number of tiller/plant			Dry matter yields (t/ha)		
	1st	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
Alamo	160.5	192.2	164.4	922	1190	1068	10.0	14.7	16.0	12.27	23.64	15.96
Blackwell	145.5	170.0	148.9	1016	1707	2252	11.4	14.2	20.3	8.22	19.00	15.14
CIR	142.2	166.7	155.5	1001	1374	1546	9.9	14.2	17.0	6.77	14.87	14.33
Kanlow	175.1	201.1	186.7	786	937	920	9.5	10.5	15.0	8.71	20.91	16.87
Pangburn	178.8	206.7	182.2	878	1002	1019	9.1	11.9	16.0	8.81	21.55	15.08
0 kg N/ha	-	191.7	160.7	-	-	1280	-	-	15.2	-	19.46	13.88
75 kg N/ha	-	187.3	164.7	-	-	1271	-	-	17.2	-	19.02	15.52
150 kg N/ha	-	183.0	177.3	-	-	1530	-	-	18.2	-	21.52	17.03
Mean	160.4	187.3	167.5	880	1242	1360	9.9	10.3	16.9	8.95	19.99	15.48

Table 5: Growth characteristics (plant height, number of tillers/m², number of tillers per plant) and dry matter yields (t/ha) in Trisaia (Italy) in 1998, 1999 and 2000.

Varieties	Final canopy height (cm)			Number of tillers/m²			Number of tiller/plant			Dry matter yields (t/ha)		
	1st	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*	*1st*	*2nd*	*3rd*
Alamo	100.3	179.0	190.0	-	1472	1179	-	10.1	12.3	4.83	15.46	17.96
Blackwell	78.3	122.0	136.7	-	765	1423	-	7.6	14.7	2.61	7.75	8.86
CIR	74.3	124.6	163.3	-	1005	1245	-	7.5	12.3	2.03	6.13	8.52
Forestburg	60.0	112.3	140.0	-	960	1467	-	11.5	26.7	0.64	4.59	6.63
Kanlow	82.7	182.3	186.7	-	765	1134	-	9.7	14.7	1.49	7.86	11.69
0 kg N/ha	-	148.4	174.0	-	1185	1387	-	11.4	13.8	-	8.16	9.95
75 kg N/ha	-	145.6	168.0	-	904	1201	-	11.6	15.2	-	8.96	11.16
150 kg N/ha	-	146.8	148.0	-	891	1281	-	9.6	17.4	-	7.96	11.09
Mean	79.1	146.9	163.3	-	993	1289	-	10.9	15.5	2.32	8.36	10.73

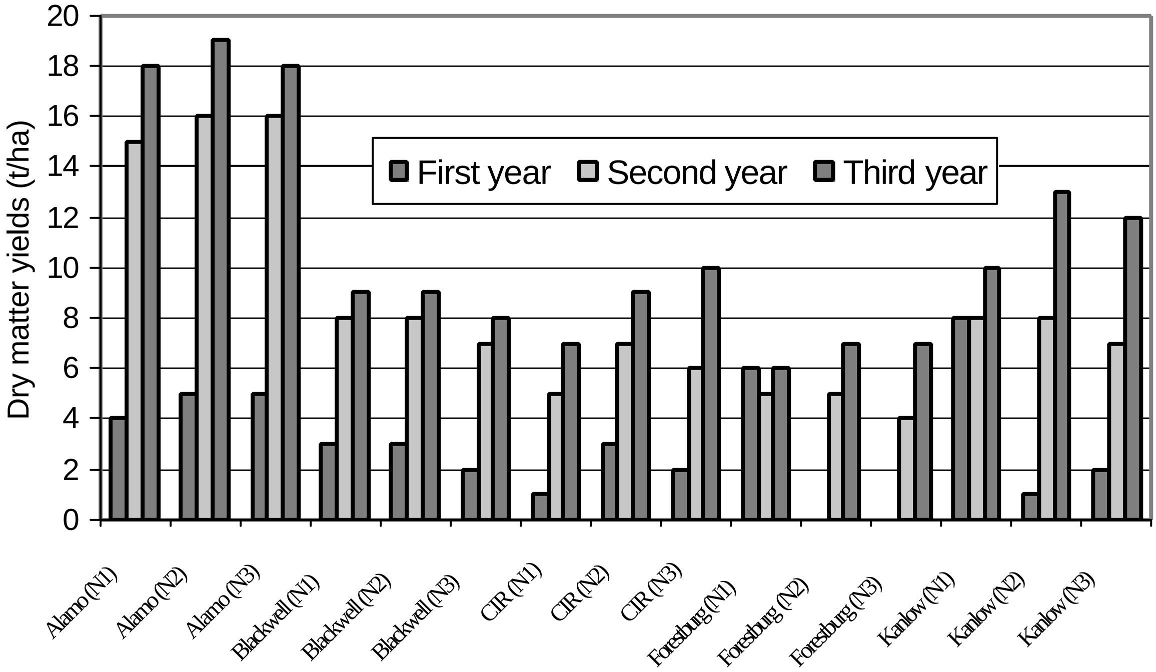

Figure 3. Dry matter yields (t/ha) for the period 1998-2000 in Trisaia (Italy).

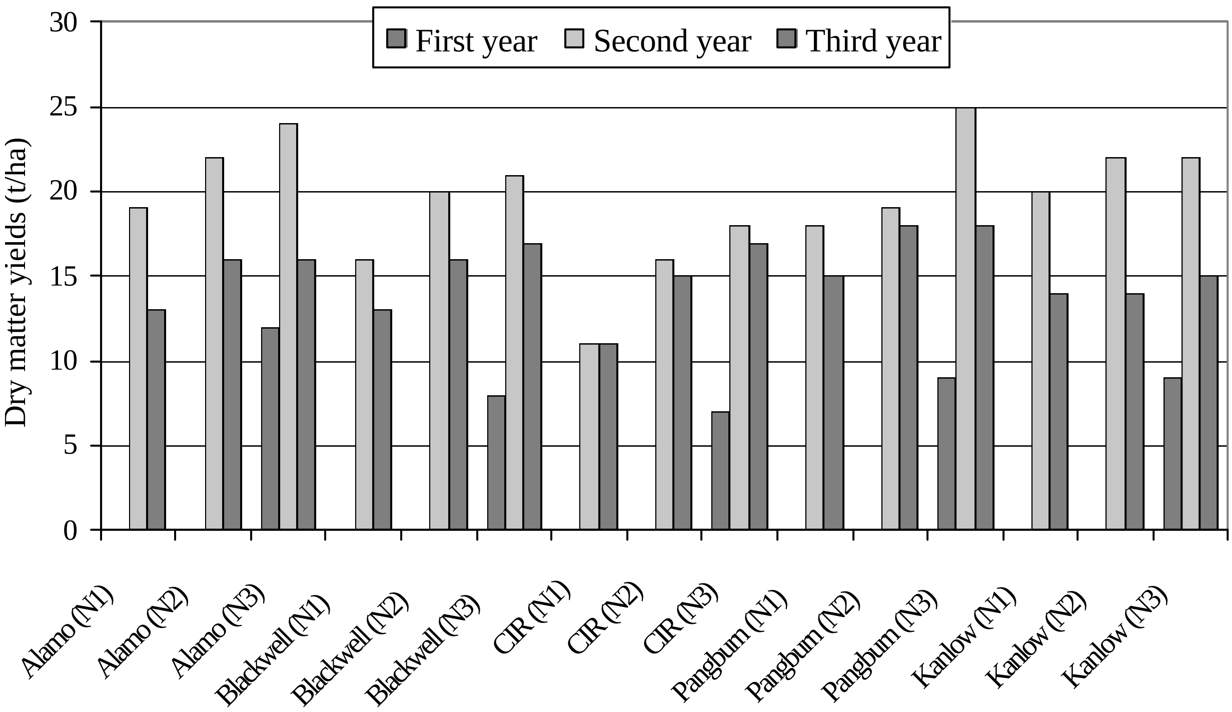

Figure 4. Dry matter yields (t/ha) for the period 1998-2000 in Aliartos (Greece).

3.5 Conclusions

Nursery trials

The adaptability and biomass productivity for the varieties was quite good in both Mediterranean countries. The only exception to that were two varieties that were cultivated in Italy (9005439 and 9005438). The establishment for these varieties was not very good and so at the establishment year the biomass productivity was quite low and for this reason they did not harvested. Their productivity improved in the following two years (1999 and 2000) but still continued to be the varieties with the smallest productivity among the tested varieties in Italy.
Comparison of the yields between the two countries showed that the most of the common tested varieties yielded higher in Greece than Italy.
It should be pointed out that in Italy the yields continued to increase until the third growing season, while in Greece the yields had been stabilised from the second growing season.
It was also noticed that peak values for dry matter yields were recorded from different varieties in each country.

Productivity trials

The establishment, a key factor for switchgrass cultivation, was quite successful in all the trials at both sites.
The weeds were a problem only during the initial stages of the first year of the experiment. Soon after the plants were able to compete with the weeds.
Regarding the effect of different nitrogen fertilisation rates, no any significant effect on fresh and dry matter yield was observed. Only in the case of the Greek trial statistically significant (LSD Test, $P<0.05$) higher yields were recorded under higher nitrogen rates during the third growing season.
Concerning the productivity, the variety Alamo in Italy and Pangburn in Greece were the most productive ones in terms of fresh and dry matter yields. On the other hand, the lowest yields in Italy were recorded in all years by the variety Forestburg, while in Greece were recorded by the variety CIR.

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4 Switchgrass nutrient composition[3]

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4.1 Introduction

Switchgrass (*Panicum virgatum* L.) is a perennial C_4 grass native to North America where it occurs naturally from 55° N latitude to deep into Mexico, mostly as a prairie grass. In North America the first varieties were selected in the 1930's for soil conservation and later as a fodder crop. Now it is also used world-wide as an ornamental plant. Since the early 1990s the crop has been developed as a model herbaceous energy crop for ethanol and electricity production in the USA and Canada. Since 1998 switchgrass is being investigated as a novel lignocellulosic C_4 biomass crop for adaptation to European conditions. Proposed uses include bioenergy, ethanol and also pulp production. The plant is best compared to other biomass grasses like *Miscanthus*, *Arundo Donax* and Reed Canary Grass. Switchgrass is propagated by seed which makes it relatively inexpensive to establish.

Nutrient analysis of switchgrass is important in order to help determine the optimum fertiliser requirements. The removal of nutrients by the plant must (in the long term) be equal to the amount of nutrients that are supplied from outside sources i.e. fertilisation of deposition.

Nutrient content of a biomass crop is a very important quality trait for thermal conversion (see Chapter 7) and for utilisation as pulp (see Chapter 7). For example the amount of ash and the composition of the ash determines the ash melting behaviour. High K and Na content of the ash m will reduce the ash melting point increasing slagging problems in the boiler. High Cl contents will lead to corrosion problems. Therefore nutrient composition determines to quite some extent the thermal conversion options which are available for switchgrass utilisation. When switchgrass is to be utilised for pulp production total ash content and composition are an important factor for reusing chemicals and high ash contents may also increase wear of the machinery.

The main objective of the research presented here was to evaluate nutrient content of switchgrass biomass in relation to growing conditions in Europe.

4.2 Methods and Materials

Site and treatments

Two types of trials were used for sampling for nutrient content. The first, nursery trial, contained some 15 switchgrass varieties in small plots. The other included 5 switchgrass varieties under two or three nitrogen stages (0, 75 and 150 kg N/ha) on larger plots. The experimental conditions and layout of the six experiments which were sampled for nutrient content are presented in Table 1. In the Dutch (NL) experiments *Miscanthus giganteus* was included for comparison.

All samples were taken from material harvest in winter or early spring when plants had senesced. Samples were dried at 105°C and stored until analysis. Nutrient analysis was conducted according to standard laboratory practices for plant analysis.

[3] This chapter is to be submitted for publication.

Table 1. Conditions and set-up of the two experiments at four countries.

	The Netherlands		UK		Germany	Greece
Experiment	Productivity	Nursery	Productivity	Nursery	Productivity	Productivity
Site	Wageningen	N.O. Polder	Rothamsted		Braunschweig	Aliartos
Latitude	51°58´	52°38´	51°48´		52°18´	40°09´
T January °C	1,8	1,4	3,1		0,4	
T July °C	16,6	17,4	15,9		17,1	
Prescipitation, mm	700	747	688		619	
Soil texture	Coarse	Fine	Moderately fine over fine		Moderately coarse over coarse	
pH	5,2	7,5	7		6,5	
Experimental layout	Randomised complete block design in three blocks				Split plot design in three blocks, with variety as main plot and N treatment as a split	Randomised complete block design in three blocks
Treatments	0 and 75 kg N/ha and 5 switchgrass varieties	13 switchgrass varieties	0 and 75 kg N/ha and 5 switchgrass varieties	15 switchgrass varieties	0, 75 and 150 kg N/ha and 5 switchgrass varieties	0, 75 and 150 kg N/ha and 5 switchgrass varieties
Plot size	8 x 6 m	4 x 3.5 m	8 x 5 m	4.5 x 2 m	7.5 x 6.5 m	6.5 x 7.5
Row distance	15 cm		14.2 cm		15 cm	
Seeding date	2-06-98	28-05-98	22-06-98		23-06-98	
Weed control	Chemical, manual, mowing	Chemical, mowing	Chemical		Chemical, manual	

4.3 Results and Discussion

In Chapters 2 and 3 details on development and yield are presented for the experiments which were sampled for nutrients. In Tables 1 and 2 average nutrient content of switchgrass varieties and the *Miscanthus* plots are presented for the experiments on clayey and on a sandy soil. In tables 3 and 4 the individual nutrient content of switchgrass varieties is given.

Effect of soil type

In the Netherlands one experiment was situated on a sandy and the other on a clay soil. The ash content of switchgrass and Miscanthus biomass was 2 to 3 times higher on the clay compared to the sandy soil. The content of other nutrients like P, K and Ca was similar for both soil types therefore a higher silica uptake on the clay soil probably explains the difference. This effect was to be expected, as it is known that on a clay soil plants take up more silica.

Switchgrass and *Miscanthus*

The average ash content of the switchgrass varieties was higher compared to *Miscanthus* after the second year at both sites (Table 1 and 2). This may be explained by higher leaf to stem ratios for switchgrass, which were probably increased by severe lodging in the third year. Though lodging is a frequent occurrence in switchgrass, the degree was probably unusual in the third year and may not be representative for switchgrass. Lodging in switchgrass is discussed in Chapter 2. Comparison between the average nutrient content of switchgrass and *Miscanthus* shows that average P levels were higher in switchgrass compared to *Miscanthus* this effect was consistent also for individual switchgrass varieties. The average K levels were lower in switchgrass compared to *Miscanthus*. This effect was even larger for early maturing varieties like Forestburg and REAP-921. The average levels of Ca and Mg were consistently higher in switchgrass compared to *Miscanthus.* The average concentration of Na in biomass was consistently lower for switchgrass compared to Miscanthus. This was also true for the higher Na containing switchgrass varieties like Pangburn. The Cl content of switchgrass was lower for all switchgrass compared to Miscanthus even when switchgrass was severely lodged (in year 3). This should contribute to lower corrosion problems when utilising switchgrass in thermal conversion compared to *Miscanthus* as discussed in Chapter 7.

This is the first comparison of switchgrass and *Miscanthus* in the same experiment. A lower K and Na combined with the higher Ca and Mg levels in biomass contribute to higher ash-melting temperatures which reduces the chance of slagging in boilers. This explains why higher ash-melting temperatures have been found for switchgrass compared to *Miscanthus* (see Chapter 7 and Christian and Riche, 1999).

Effect of nitrogen

The effect of nitrogen stage on can be observed in Tables 2 and 4 to 7.
In the Netherlands, The UK and in Greece no effect of nitrogen on yield could be observed. In Germany higher N stages clearly increased yields, though overall yields were lower than at other sites. Higher nitrogen fertiliser rates increased nitrogen content of the biomass at all the sites, especially when N was increased from 0 to 75 kg N/ha. Other effects were less evident. At the two sites in the Netherlands consistently higher K, Mg and Cl concentrations were found in the switchgrass biomass at the high nitrogen rate (75 kg N/ha) compared to the control. Other effects were generally inconsistent.

Leaf and stem comparisons

In the experiments at Aliartos (GR) and Rothamsted (UK) leaves and stems were analysed for nutrients separately (Table 5 and 7).
The ash content of leaves was up to five times higher in leaves compared to stems (Table 5). The N, P, Ca, and Mg concentrations were consistently higher in leaves compared to stems both in Greece and the UK. The K concentrations were consistently lower in leaves compared to stems both in Greece and the UK. This effect may be due to the ease of leaching of the very soluble K compared to immobile nutrients like Ca, Mg and P.

The Na concentration tended to be very high in Greece compared to the other sites. This may be explained by salt accumulation in the soil due to irrigation.

The higher ash and nutrient content of leaves compared to stems illustrates the importance of leaf to stem ratios. This trait is different between varieties (see Table 7) and will decrease as plants mature and loose leaves over winter. Therefore varieties with low leaf to stem ratios that mature early will have comparatively lower ash and nutrient contents which increases biomass quality. Bio-refining of switchgrass into leaf and stem fractions has been proposed in order to increase quality for thermal conversion and pulp production.

Variability between switchgrass varieties

A wide variety of switchgrass varieties was used in the different experiments. These varieties differed in many ways including seed size, seed vigour, establishment success, growth habit, and latitude at which they originated which determines the time too flowering and time of maturation. All these and many other attributes contribute to differences in nutrient content of the biomass at harvest in winter.
When plants mature in fall many nutrients are translocated to the underground parts of the plants. This is specifically the case for nutrients that are easily translocated like K and N. Other nutrients like P and Ca are generally less mobile. Another factor is the loss of leaves during the maturation process, which returns nutrients to the soil.

In Figures 1 and 2 the concentration of the most important nutrients of the whole biomass (Figure 1) or leaves and stems (Figure 2) is plotted against the latitude where the switchgrass varieties originated. We see that for N, P, K and Cl there is a consistent negative correlation with latitude of origin. This means that switchgrass varieties originating at northern areas have lower N, P, K and Cl concentrations than varieties originating at southern sites. In the third year the relationship was less pronounced possibly due to lodging of the crop which prevented proper maturation and translocation of nutrients.

In Figure 2 the leaves and stems are regarded separately. Here also N, P, and K and also Mg and Na concentrations are lower in northern compared to southern varieties both in leaves and in stems. For Ca the concentration seems to be higher in leaves of northern varieties.

Nutrient off-take

Nutrient off-take is presented in Tables 1 to 5 and 7. In the Netherlands the N take-off for the most promising switchgrass variety Cave-in-Rock varied between 10 kg/ha I the first year and 111 kg/ha in the third year when the crop lodged severely. In Germany where yields were lower N off-take was between 17 and 56 kg/ha for Cave-in-Rock as the N stage increased from 0 to 150 kg N/ha. At Rothamsted The offtake of Cave-in-Rock amounted to some 60 kgN /ha at which yield were obtained of 15 tonnes /ha. No N response was apparent. Lodging was also reported at the Rothamsted site but was less severe than in The Netherlands.

4.4 Conclusions

The results show that switchgrass biomass has lower K, Na and Cl concentrations compared to *Miscanthus*.
The concentrations of N and Ca were higher in switchgrass compared to *Miscanthus*.
At harvest in winter the concentration of N, P, K and Cl was lower in varieties originating at northern regions compared to varieties originating at southern regions.
At yields of some 15 tonnes of dry matter the N off-take was some 60 kg/ha should be expected for currently available well-adapted varieties.
N and also P and K off-take will be increased by lodging.

Table 1. Wageningen (NL) sandy site. Ash and nutrient content of 12 switchgrass varieties and Miscanthus gigantheus over first 3 years. Samples are mix of 3 plots. The plots were seeded in spring 1998 and harvested on 17 March 1999, 12 January 2000 and 6 March 2001.

	Year	DM yield	Ash	N	P	K	Ca	Mg	Na	Cl	N	P	K
		tonne/ha	g/kg								kg/ha		
Switchgrass	1	0.93	34.9	16.63	1.55	2.10	3.25	1.14	85	-----	15.4	1.4	1.9
Miscanthus	1	0.19	36.0	9.40	0.85	2.40	1.33	0.90	287	-----	1.7	0.2	0.4
Switchgrass	2	6.7	21.3	5.01	0.64	2.55	3.80	1.17	107	1.01	33.8	4.3	17.2
Miscanthus	2	2.9	10.0	2.74	0.35	5.26	0.97	0.64	308	3.55	8.0	1.0	15.4
Switchgrass	3	12.8	21.5	7.46	0.92	2.54	2.92	1.15	83	0.42	95.4	11.7	32.5
Miscanthus	3	14.0	12.0	2.39	0.48	2.06	1.34	0.53	139	0.58	33.4	6.7	28.8

Table 2. Noordoostpolder (NL), clay site. Average ash and nutrient content of 5 switchgrass varieties and *Miscanthus gigantheus* under 0 and 75 kg N/ha over first 3 years. The plots were seeded in spring 1998 and harvested on 18 March 1999, 25 January 2000 and 20 February 2001.

Species	N trt	Year	Yield	Ash		N		P		K		Ca		Mg		Na		Cl		N	P	K
	kg N/ha		Tonne/ha	g/kg ±STD																kg/ha		
Switchgrass	0	1	0.38	97.6	----	17.67	----	1.79	----	2.42	----	5.75	----	1.19	----	0.125	----	----	----	6.7	0.68	0.92
Miscanthus	0	1	----	154.0	----	15.90	----	1.37	----	2.47	----	6.03	----	1.45	----	0.191	----	----	----			
Switchgrass	0	2	4.76	57.3	8.8	4.04	0.85	0.60	0.12	2.41	1.61	4.26	0.92	0.85	0.13	0.266	0.049	0.72	0.48	19.2	2.87	11.49
Switchgrass	75	2	5.07	52.3	6.9	6.24	1.68	0.69	0.22	3.45	2.07	4.41	0.58	0.98	0.15	0.281	0.064	0.82	0.47	31.6	3.51	17.47
Miscanthus	0	2	0.98	58.7	6.4	4.58	0.69	0.41	0.04	6.50	0.79	1.60	0.21	0.52	0.12	0.738	0.305	3.33	0.44	4.5	0.40	6.37
Miscanthus	75	2	1.18	60.0	6.0	4.85	1.51	0.48	0.09	7.72	0.41	1.57	0.25	0.62	0.14	0.744	0.274	3.97	0.55	5.7	0.57	9.13
Switchgrass	0	3	9.70	75.8	22.8	6.17	2.35	0.83	0.29	2.59	0.91	4.34	1.70	0.84	0.30	0.125	0.058	0.58	0.38	59.9	8.07	25.16
Switchgrass	75	3	8.27	80.6	26.9	8.37	3.23	0.92	0.38	3.15	0.87	5.01	2.10	0.98	0.36	0.130	0.050	0.67	0.39	69.3	7.59	26.02
Miscanthus	0	3	40.62	31.3	3.1	1.53	0.20	0.26	0.08	3.43	0.55	0.73	0.07	0.25	0.01	0.246	0.013	1.33	0.13	62.0	10.39	139.26
Miscanthus	75	3	49.85	31.3	4.2	1.75	0.12	0.14	0.01	3.81	0.82	0.76	0.03	0.33	0.02	0.234	0.018	1.42	0.30	87.1	7.12	189.86

STD = standard deviation

Table 3. Wageningen (NL) sandy site. Ash and nutrient content of switchgrass varieties over first 3 years. Plots were seeded in spring 1998 and harvested on 17 March 1999, 12 January 2000 and 6 March 2001.

Variety	Year	Yield	Ash	N	P	K	Ca	Mg	Na	Cl	N	P	K
		tonne/ha	g/kg								kg/ha		
Blackwell	1	1.26	34.0	17.41	1.64	2.19	3.42	1.33	0.084	---	22.0	2.1	2.8
Caddo	1	1.23	30.0	17.38	1.72	2.58	3.02	1.17	0.090	---	21.4	2.1	3.2
Carthage	1	0.82	28.0	18.05	1.66	1.58	2.76	1.06	0.058	---	14.8	1.4	1.3
CIR	1	1.24	34.0	15.20	1.36	1.78	2.80	1.18	0.081	---	18.9	1.7	2.2
Forestburg	1	0.47	66.0	14.52	1.14	2.05	3.68	1.04	0.107	---	6.9	0.5	1.0
Kanlow	1	1.13	30.0	18.79	1.85	2.00	3.32	1.43	0.065	---	21.3	2.1	2.3
NU 94-2	1	1.10	34.0	15.94	1.42	1.63	2.91	1.10	0.087	---	17.5	1.6	1.8
Pangburn	1	0.86	36.0	18.92	2.00	2.13	3.59	1.22	0.073	---	16.3	1.7	1.8
Reap 921	1	0.26	28.0	15.24	1.37	1.86	2.93	1.02	0.090	---	4.0	0.4	0.5
Shelter	1	0.95	34.0	14.95	1.29	1.59	4.07	0.96	0.068	---	14.2	1.2	1.5
Summer	1	0.85	30.0	16.50	1.61	3.68	3.26	1.08	0.130	---	14.1	1.4	3.1
Blackwell	2	8.21	26.0	4.66	0.66	2.34	3.94	1.30	0.110	0.83	38.3	5.4	19.2
Caddo	2	8.08	26.0	4.80	0.61	2.09	3.90	1.12	0.104	0.88	38.8	4.9	16.9
Carthage	2	6.53	26.0	5.86	0.75	3.31	3.38	1.25	0.113	0.83	38.3	4.9	21.6
CIR	2	9.23	22.0	4.56	0.58	2.46	4.27	1.30	0.103	1.10	42.1	5.3	22.7
Forestburg	2	6.07	16.0	4.26	0.61	1.36	3.86	0.88	0.080	0.41	25.8	3.7	8.2
Kanlow	2	6.08	20.0	6.33	0.88	5.45	2.52	1.37	0.091	2.27	38.5	5.3	33.2
NU 94-2	2	8.22	14.0	4.20	0.48	2.49	3.82	1.10	0.185	1.11	34.5	3.9	20.5
Pangburn	2	4.28	26.0	7.20	0.77	5.35	2.89	1.23	0.169	2.77	30.9	3.3	22.9
Reap 921	2	4.45	18.0	3.81	0.53	0.86	3.76	0.96	0.068	0.21	17.0	2.4	3.8
Shelter	2	6.82	22.0	5.11	0.56	1.28	4.84	1.25	0.077	0.41	34.9	3.8	8.7
Summer	2	6.24	18.0	4.31	0.58	1.03	4.64	1.11	0.076	0.27	26.9	3.6	6.4
Blackwell	3	10.05	26.0	9.11	1.13	2.70	3.07	1.19	0.083	0.49	91.6	11.4	27.2
Caddo	3	10.16	20.0	9.31	1.13	2.92	3.05	1.38	0.094	0.38	94.6	11.5	29.6
Carthage	3	16.02	20.0	7.39	0.99	2.72	2.61	1.12	0.074	0.52	118.3	15.8	43.6
CIR	3	13.80	12.0	8.05	0.86	2.76	2.91	1.10	0.089	0.46	111.1	11.9	38.1
Forestburg	3	8.63	22.0	7.37	0.83	1.40	2.96	0.87	0.065	0.23	63.6	7.2	12.1
Kanlow	3	17.54	22.0	6.54	1.01	4.37	2.17	1.44	0.090	0.76	114.8	17.8	76.6
NU 94-2	3	15.19	24.0	8.21	0.91	2.24	3.25	1.30	0.095	0.41	124.7	13.9	34.0
Pangburn	3	12.57	28.0	6.83	1.00	4.07	2.52	1.21	0.109	0.74	85.9	12.6	51.2
Reap 921	3	11.47	18.0	5.85	0.63	1.29	2.35	0.90	0.069	0.16	67.0	7.2	14.8
Shelter	3	12.81	22.0	6.19	0.76	1.45	4.26	1.10	0.068	0.20	79.2	9.7	18.5
Summer	3	12.44	22.0	7.22	0.81	2.03	2.95	1.09	0.078	0.24	89.8	10.0	25.2

Table 4. Noordoostpolder (NL), clay site. Ash and nutrient content and Nutrient offtake per ha of switchgrass varieties over first 3 years under 0, 75 or 150 kg N /ha per year. The plots were seeded in spring 1998 and harvested on 18 March 1999, 25 January 2000 and 20 February 2001.

Variety	N trt	Year	Yield	Ash		N		P		K		Ca		Mg		Na		Cl		N	P	K
	kg N/ha		Tonne/ha	g/kg ±STD																kg/ha		
Blackwell	0	1	0.48	102.0	--	17.82	--	1.79	--	2.08	--	6.32	--	1.18	--	0.102	--	--	--	8.5	0.86	1.00
Carthage	0	1	0.21	104.0	--	19.52	--	2.05	--	2.48	--	6.25	--	1.26	--	0.099	--	--	--	4.1	0.43	0.52
CIR	0	1	0.64	86.0	--	17.24	--	1.68	--	2.03	--	5.65	--	1.23	--	0.101	--	--	--	11.0	1.07	1.30
Forestburg	0	1	0.16	104.0	--	17.11	--	1.61	--	3.05	--	5.17	--	1.21	--	0.201	--	--	--	2.7	0.25	0.47
Summer	0	1	0.30	92.0	--	16.68	--	1.81	--	2.43	--	5.36	--	1.08	--	0.122	--	--	--	5.0	0.54	0.73
Blackwell	0	2	5.09	59.3	5.0	3.88	0.17	0.61	0.04	2.48	0.32	3.67	0.68	0.87	0.02	0.252	0.034	0.82	0.11	19.7	3.12	12.63
Blackwell	75	2	5.60	56.7	5.0	6.67	1.52	0.77	0.12	3.38	0.32	4.15	0.26	1.03	0.11	0.244	0.021	0.90	0.08	37.3	4.32	18.92
Carthage	0	2	5.56	52.0	8.0	5.42	0.71	0.77	0.15	5.03	0.53	3.18	0.80	0.96	0.21	0.307	0.057	1.49	0.11	30.1	4.30	27.98
Carthage	75	2	5.45	54.0	4.0	7.71	0.58	0.99	0.07	6.19	1.09	3.55	0.26	1.14	0.08	0.233	0.038	1.47	0.17	42.0	5.38	33.73
CIR	0	2	5.29	54.7	4.2	3.70	0.42	0.49	0.06	2.77	0.54	4.24	0.48	0.86	0.02	0.213	0.014	0.74	0.13	19.6	2.61	14.66
CIR	75	2	5.66	57.3	6.1	7.62	1.21	0.73	0.16	4.87	1.18	4.72	0.33	0.98	0.08	0.324	0.082	1.07	0.11	43.1	4.14	27.54
CIR	150	2	5.34	53.3	2.3	8.76	0.87	0.78	0.10	5.49	0.85	3.90	0.18	1.02	0.07	0.294	0.096	1.11	0.03	46.7	4.16	29.27
Forestburg	0	2	3.44	68.7	11.5	3.92	0.60	0.60	0.05	0.93	0.17	5.17	0.25	0.78	0.13	0.264	0.044	0.27	0.04	13.5	2.05	3.19
Forestburg	75	2	3.75	48.0	8.7	4.34	0.62	0.44	0.01	1.20	0.40	4.84	0.30	0.79	0.15	0.355	0.037	0.37	0.01	16.3	1.67	4.50
Summer	0	2	4.41	52.0	2.0	3.27	0.04	0.54	0.04	0.86	0.15	5.06	0.07	0.77	0.13	0.295	0.044	0.26	0.02	14.4	2.39	3.81
Summer	75	2	4.88	45.3	3.1	4.84	0.76	0.53	0.10	1.59	0.45	4.78	0.39	0.95	0.13	0.248	0.029	0.28	0.09	23.6	2.59	7.77
Blackwell	0	3	10.03	94.0	4.0	6.97	0.24	0.95	0.02	1.96	0.14	4.65	0.27	0.98	0.08	0.110	0.030	0.38	0.05	70.0	9.57	19.63
Blackwell	75	3	7.54	110.0	12.2	10.13	0.49	1.11	0.10	3.27	0.69	6.20	1.23	1.30	0.28	0.120	0.012	0.64	0.20	76.4	8.38	24.64
Carthage	0	3	11.39	81.3	16.8	8.31	0.49	1.10	0.07	3.42	0.10	4.79	0.45	1.17	0.17	0.109	0.002	0.57	0.07	94.6	12.55	38.92
Carthage	75	3	10.10	88.7	16.2	9.36	0.47	1.14	0.03	3.28	0.44	5.13	0.82	1.22	0.03	0.114	0.010	0.52	0.10	94.5	11.55	33.14
CIR	0	3	10.08	77.3	4.6	6.83	0.47	0.91	0.05	3.33	0.77	5.04	0.30	0.89	0.06	0.104	0.002	0.60	0.21	68.8	9.13	33.52
CIR	75	3	8.58	92.7	8.1	10.86	0.98	1.14	0.12	3.95	0.42	6.08	0.91	1.13	0.18	0.112	0.010	0.63	0.15	93.2	9.77	33.87
CIR	150	3	9.14	85.3	5.0	10.97	0.87	1.11	0.14	3.14	0.55	5.90	0.15	1.09	0.06	0.114	0.011	0.55	0.13	100.3	10.17	28.70
Forestburg	0	3	7.14	91.3	6.4	6.79	1.77	0.86	0.18	1.59	0.33	5.34	0.15	0.86	0.03	0.096	0.006	0.31	0.08	48.5	6.14	11.38
Forestburg	75	3	5.04	86.7	15.3	8.30	1.56	0.89	0.14	1.88	0.43	5.66	0.51	0.86	0.11	0.097	0.010	0.39	0.08	41.8	4.50	9.45
Summer	0	3	9.88	79.3	13.0	6.62	1.17	0.91	0.14	1.83	0.42	5.50	0.16	0.92	0.06	0.083	0.008	0.26	0.04	65.4	8.99	18.09
Summer	75	3	10.10	74.0	7.2	9.84	0.35	1.08	0.11	2.69	0.64	6.25	0.59	1.08	0.13	0.102	0.013	0.41	0.15	99.4	10.87	27.21

std = standard deviation

Table 5. Braunschweig, Germany. Nutrient content and off-take per ha of switchgrass varieties under 3 nitrogen stages over the three first growing seasons. Plants were harvested after a killing frost in late winter.

Variety	N trt	Year	Yield	N	P	K	Ca	Mg	N	P	K
			tonne/ha	g/kg					kg/ha		
Blackwell	0	1	1.6	17.67	2.47	4.83	14.07		28.8	4.0	7.9
Carthage	0	1	1.5	13.87	1.99	4.46	8.66	1.58	20.8	3.0	6.7
CIR	0	1	1.0	15.70	2.20	3.87	8.37		16.1	2.3	4.0
Forestburg	0	1	0.6	14.30	1.87	5.30	9.20		7.8	1.0	2.9
Summer	0	1	0.5	17.60	1.97	4.50	12.77		9.5	1.1	2.4
									0.0	0.0	0.0
CIR	0	2	2.5	6.90	1.36	4.40	14.33	0.78	17.0	3.3	10.8
CIR	75	2	2.8	7.10	1.41	4.48	13.61	0.84	19.8	3.9	12.5
CIR	150	2	3.8	7.10	1.19	4.57	13.18	1.08	27.3	4.6	17.5
									0.0	0.0	0.0
Blackwell	0	3	5.0	5.20	0.80	2.20	7.13		25.9	4.0	11.0
Blackwell	75	3	6.3	5.80	0.70	2.20	8.00		36.4	4.4	13.8
Blackwell	150	3	8.1	6.00	0.60	2.40	7.60		48.4	4.8	19.4
Carthage	0	3	4.8	7.40	0.70	2.08	7.92	0.54	35.4	3.4	10.0
Carthage	75	3	7.3	8.10	0.66	1.74	7.70	0.60	59.1	4.8	12.7
Carthage	150	3	8.5	6.40	0.57	2.16	7.92	0.72	54.4	4.8	18.4
CIR	0	3	3.2	5.40	0.60	2.20	7.70		17.4	1.9	7.1
CIR	75	3	6.7	6.10	0.50	2.40	7.60		40.7	3.3	16.0
CIR	150	3	7.8	7.10	0.60	2.30	7.20		55.5	4.7	18.0
Forestburg	0	3	4.2	5.30	0.70	1.80	8.50		22.5	3.0	7.6
Forestburg	75	3	6.4	6.00	0.70	1.50	8.40		38.5	4.5	9.6
Forestburg	150	3	8.0	6.10	0.80	1.50	9.70		48.5	6.4	11.9
Summer	0	3	4.5	5.50	0.70	1.70	7.60		24.6	3.1	7.6
Summer	75	3	7.2	5.70	0.70	1.50	8.40		41.0	5.0	10.8
Summer	150	3	7.6	6.30	0.80	1.30	9.60		47.8	6.1	9.9
Average	0	3	4.3	5.76	0.70	2.00	7.77		25.2	3.1	8.7
Average	75	3	6.8	6.34	0.65	1.87	8.02		43.2	4.4	12.6
Average	150	3	8.0	6.38	0.67	1.93	8.40		50.9	5.4	15.5

Table 6. Aliartos, Greece. Ash and nutrient content of leaves and stems of switchgrass varieties Alamo and Cave in Rock over the second and third growing season. Harvested after over-wintering on 31 January 2000 and 13 January 2001.

		Leaves							Stems						
Variety	N trt	Ash	N	P	K	Ca	Mg	Na	Ash	N	P	K	Ca	Mg	Na
31 January 2000		g/kg													
Alamo	0	83.5	2.71	0.39	3.40	13.38	2.38	1.89	18.4	0.89	0.28	4.39	4.25	0.88	2.22
Alamo	75	82.5	3.52	0.34	3.89	15.38	2.50	1.72	24.7	1.40	0.23	3.99	3.38	1.00	2.38
Alamo	150	92.3	5.58	0.68	4.43	9.63	5.88	2.55	19.4	1.54	0.30	5.02	2.88	0.75	2.22
Cave in Rock	0	99.5	2.24	0.35	2.57	13.50	1.63	1.56	22.3	0.84	0.18	2.67	4.75	0.50	1.39
Cave in Rock	75	106.4	2.88	0.55	2.86	18.88	2.25	1.89	18.4	0.84	0.17	3.35	3.50	0.50	1.39
Cave in Rock	150	97.9	4.06	0.43	3.11	15.75	2.00	1.72	22.4	0.85	0.32	4.39	3.63	0.63	1.72
13 January 2001															
Alamo	0	77.7	2.89	0.45	2.96	12.00	1.50	1.89	18.3	1.14	0.30	4.88	4.25	1.00	2.22
Alamo	75	84.2	3.66	0.39	2.23	8.75	1.63	1.39	18.9	1.15	0.19	3.99	3.63	1.00	1.89
Alamo	150	77.2	4.31	0.48	3.70	13.38	2.13	2.05	18.8	1.74	0.27	3.94	3.88	1.13	2.05
Cave in Rock	0	77.4	3.17	0.43	2.57	13.38	1.50	2.05	15.1	1.05	0.23	3.40	3.75	0.75	1.39
Cave in Rock	75	81.2	4.19	0.58	3.65	13.50	2.00	2.05	16.1	1.10	0.27	4.29	4.00	0.88	1.89
Cave in Rock	150	87.4	4.33	0.38	3.16	13.88	1.50	1.72	18.5	1.33	0.17	3.50	5.00	0.88	1.72

Table 7. Rothamsted (UK). Nutrient content and nutrient off-take of switchgrass varieties after the third growing season for a small plot experiment (Nursery trial) and for a larger plot field experiment (Yield trial) with implementation of a nitrogen stage (0 and 75 kg N/ha). The nursery trial was harvested in winter on 16-01-2001 and the yield trial was harvested 13-02-2001.

			Leaf						Stem						Total off-take		
Treatment	L/S*	DM	N	P	K	Ca	Mg	Na	N	P	K	Ca	Mg	Na	N	P	K
Nursery trial	ratio	Tonne/ha	g/kg												kg/tonne		
Alamo	0.35	16.7	11.73	1.30	3.76	8.22	2.58	0.32	5.17	0.74	8.84	1.06	1.03	0.28	114.9	14.8	125.8
Blackwell	0.33	12.1	7.71	0.72	1.32	11.99	1.38	0.30	3.04	0.42	2.38	1.73	0.60	0.16	50.9	6.0	25.6
Caddo	0.23	12.1	7.74	0.76	1.17	10.85	1.12	0.29	2.96	0.41	2.44	1.59	0.54	0.19	46.9	5.8	26.6
Cave in rock	0.30	15.3	7.09	0.62	1.22	8.89	1.01	0.22	3.33	0.42	3.82	1.19	0.33	0.16	64.2	7.1	49.3
Forestburg	0.23	11.6	7.26	0.59	0.89	13.70	1.00	0.32	2.17	0.20	1.21	1.32	0.43	0.17	36.4	3.2	13.4
Kanlow	0.32	18.5	8.40	0.80	2.89	7.99	2.06	0.32	4.53	0.59	6.22	1.59	1.07	0.17	100.9	11.9	100.2
Nebraska 28	0.33	11.1	6.28	0.68	0.87	10.84	0.80	0.19	2.60	0.42	2.03	1.62	0.47	0.10	39.1	5.4	19.4
NL 93-1	0.25	9.0	12.42	1.02	3.13	9.50	1.94	0.50	5.05	0.56	6.48	1.65	0.88	0.18	58.7	5.9	52.3
NL 93-2	0.32	18.9	9.74	0.78	2.47	9.41	1.99	0.48	5.35	0.57	5.70	2.01	1.07	0.29	121.0	11.7	93.1
NU 94-2	0.37	15.1	8.64	0.85	1.51	10.15	1.29	0.17	3.70	0.45	3.55	1.78	0.56	0.10	76.0	8.4	45.3
Reap 921	0.19	12.0	6.94	0.53	0.92	11.17	0.89	0.28	2.86	0.27	2.22	1.24	0.36	0.15	42.2	3.7	24.2
Shelter	0.33	12.9	7.21	0.49	0.76	13.76	0.91	0.19	2.50	0.20	1.24	1.77	0.31	0.10	47.4	3.5	14.4
Su 94-1	0.27	14.2	10.42	1.29	1.76	9.66	1.34	0.23	3.57	0.57	3.14	1.84	0.70	0.13	71.2	10.2	40.4
9005439	0.18	10.3	7.03	0.56	0.95	14.60	0.77	0.28	2.41	0.24	1.07	1.89	0.37	0.20	31.9	3.0	10.8
9005438	0.18	10.7	6.47	0.65	0.76	15.27	0.78	0.26	2.02	0.32	1.30	1.44	0.36	0.11	28.8	3.9	13.1
Yield Trial																	
Cave in rock 0N	0.21	14.9	6.81	0.55	0.78	8.37	1.21	0.07	3.51	0.34	1.74	0.99	0.46	0.07	60.9	5.6	23.4
Cave in rock 75N	0.18	12.8	6.77	0.36	0.64	6.50	0.92	0.05	3.74	0.26	2.68	0.66	0.34	0.06	53.7	3.5	30.4
Carthage 0N	0.16	17.2	9.09	0.79	0.92	5.88	1.04	0.07	4.79	0.58	2.15	1.26	0.71	0.09	92.6	10.4	34.1
Carthage 75 N	0.23	12.0	9.69	0.88	0.98	6.61	1.28	0.05	4.85	0.48	2.14	1.14	0.67	0.07	69.0	6.6	23.1

* L/S = Leaf to stem ratio.

Figure 1. Relationship between the latitude of origin of 5 switchgrass varieties (Forestburg, 44°N; Summer, 41°N; Cave in Rock 38°N,;Blackwell 37° N; Carthage 35°N) and the nutrient content of the harvested biomass over the second (1999) and third (2000) growing season on a clay (Noordoostpolder) and a sandy (Wageningen) site in The Netherlands.

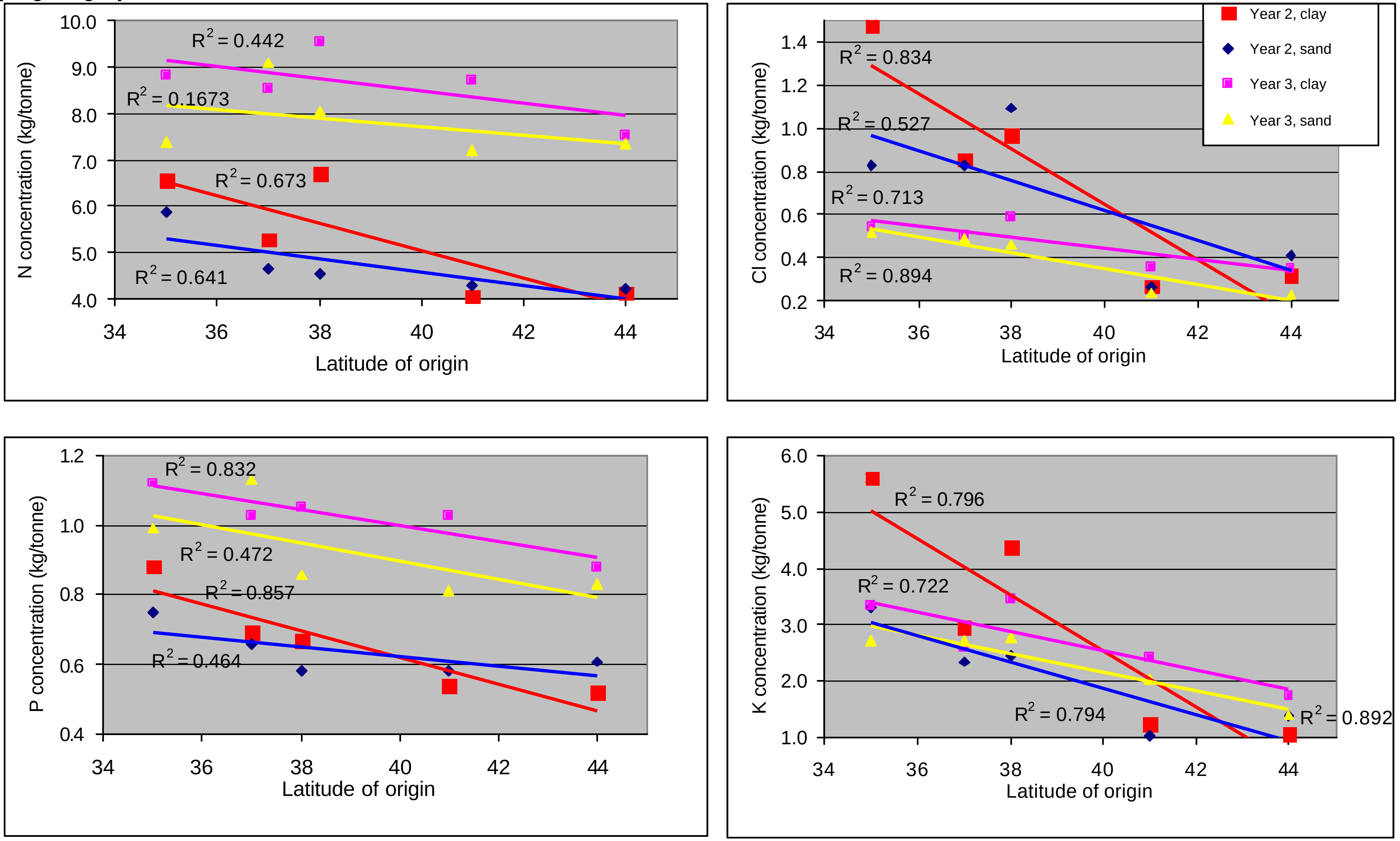
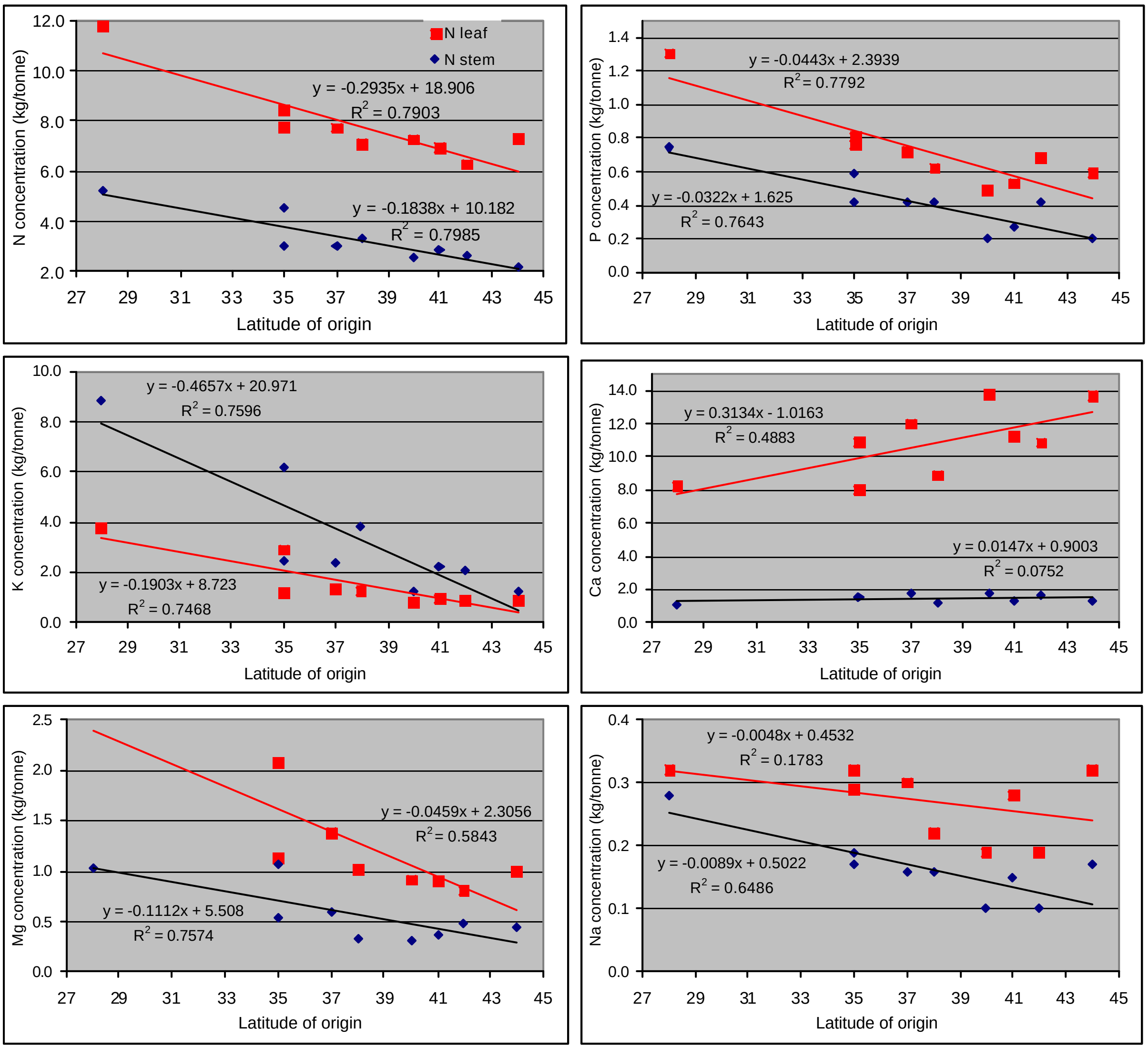


Figure 2. Rothamsted (UK). Relationship between the latitude of origin of 9 switchgrass varieties (Alamo, 28 °N; Blackwell 37° N; Caddo, 35°N; Cave in Rock 38°N; Forestburg, 44°N; Kanlow 35°N, Nebrasca28, 42°N; Reap- 921 41°N; Shelter, 40°N) and the nutrient content of leaves and stems harvested in winter after the third growing season at Rothamsted (UK).



5 Switchgrass variety choice in Europe[4]

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5.1 Summary

Switchgrass is a perennial C_4 grass native to North America, where it occurs naturally from 55º N latitude to deep into Mexico. It is used for soil conservation, forage production, as an ornamental grass and more recently as a biomass crop for ethanol, fibre, electricity and heat production. In Europe research into the crop has just started and the choice of varieties for different geographical areas is an important issue. Some 20 different varieties have been evaluated for adaptation to different regions of Europe. The main factor determining area of adaptation of a variety is latitude of origin. Yields of varieties are correlated to the latitude of origin of the variety, with southern varieties having higher yield potential. If varieties are grown too far north they fail to winter-harden which decreases biomass quality (high nutrient and moisture content) and winter survival. It appears that in Europe switchgrass may be grown further north than in North America. The best variety for a given latitude or geographical area will be a compromise between yield and quality and long term winter survival.

Key words: Switchgrass, *Panicum virgatum*, quality, latitude, mineral composition.

5.2 Introduction

Switchgrass (*Panicum virgatum* L.) is a perennial C_4 grass native to North America where it occurs naturally from 55º N latitude to deep into Mexico, mostly as a prairie grass. In North America it has been used for more than 50 years for soil conservation, as a fodder crop and as an ornamental grass. Over the last two decades it has become an important warm-season pasture grass for fodder production when cool season C_3 grasses are less productive in summer (Moser and Vogel, 1995). Since the early 1990s the crop has been developed by the United States Department of Energy (DOE) as a model herbaceous energy crop for ethanol and electricity production. In Canada, Resource Efficient Agricultural Production (REAP) has worked on switchgrass since 1991 for thermal conversion (electricity and heat) and ethanol production and is involved in projects to use switchgrass for paper pulp production. Many reasons are given for using switchgrass as a biomass crop for energy and fibre production. These include the high net biomass production per ha, low production costs, low nutrient requirement, relatively low ash content, high water use efficiency, large range of geographic adaptation, ease of establishment by seed, adaptation to marginal soils, and potential for carbon storage in soil, (Christian and Elbersen, 1998; Samson and Omielan, 1992, Sanderson et al., 1996). In Europe research into the use as a biomass crop for energy and fibre has only just started. The crop has the potential to play a role in supporting policies to increase the use of durable products, reduce CO_2 emissions, utilise marginal and set aside lands and provide new economic activities for rural communities. Over the last years many larger and smaller individual field evaluations of switchgrass have been conducted (Christian and Elbersen, 1998; Lewandowski et al., 1998). We estimate that in Europe some 4 ha of experimental switchgrass fields exist of which 2.5 ha is within the current European Union sponsored switchgrass productivity network. In this network 6 organisations co-operate in evaluating the agronomic, fibre and energy potential of more than 20 switchgrass varieties under European conditions. The data from this project have been used in the current Chapter. Here we will discuss the important issue of allocation of varieties in relation to latitude of origin of the variety and the effect on establishment, yield and quality for energy production.

[4] This chapter is to be submitted for publication.

5.3 Available switchgrass material

Ecotypes

Two switchgrass ecotypes are generally defined based on morphological characteristics and habitat preferences. Lowland types are generally found in floodplains. They are taller, coarse, have a more bunch type growth habit, and may be more rapid growing than upland types. Upland types are found in drier upland sites. They are finer stemmed, and often semi-decumbent (Moser and Vogel, 1995; Porter, 1966). Artificial hybridization between lowlands and uplands have largely been unsuccessful (Taliaferro and Hopkins, 1997). Switchgrass is highly polymorphic and largely self incompatible (Talbert et al., 1983; Taliaferro and Hopkins, 1997). The basic chromosome number of switchgrass is x = 9. The ploidy levels of switchgrass range from diploid (2n=18) to duodecaploid (2n=108) (Hulquist et al., 1996; McMillan, 1959; Nielsen, 1944; Riley and Vogel, 1982). Most varieties are tetraploid or octoploid. Switchgrass varieties have been developed since the 1930s. In Table 1 the ploidy levels of available switchgrass varieties are given.

Varieties

Early varieties like Blackwell and Nebraska-28 are wild accessions that showed good performance and were released without additional breeding work (Moser and Vogel, 1995). The earlier varieties were mostly selected for soil conservation purposes, for example Dacotah and Alamo. More recent varieties have been developed by breeding for establishment, yield, quality, and disease resistance (Moser and Vogel, 1995; Sanderson et al., 1996). Currently breeding takes place at several locations in North America. New lowland and upland varieties are being developed specifically for biomass production for biofuel (Taliaferro and Hopkins, 1997). The high genetic variation for important traits should make development of improved varieties for several purposes possible.

Table 1. Ecotype, ploidy level, origin, and seed weight of available switchgrass varieties.

Variety	Ecotype	Ploidy level	Origin	Seed weight†
Alamo	lowland	Tetraploid	South Texas 28°	94
Blackwell	upland	Octoploid	Northern Oklahoma 37°	142
Caddo	upland	Octoploid	South Great plains 35°	159
Carthage = NJ-50	?	?	North Carolina 35°	148
Cave-in-Rock	Intermediate?	Octoploid	Southern Illinois 38°	166
Dacotah	upland	Tetraploid?	North Dakota 46°	148
Forestburg	upland	Tetraploid?	South Dakota 44°	146
Kanlow	lowland	Tetraploid	Central Oklahoma 35°	85
Nebraska 28	upland	?	Northern Nebraska 42°	162
Pangburn	lowland	Tetraploid	Arkansas 34°	96
Pathfinder	upland	Octoploid	Nebraska / Kansas 40°	187
REAP 921	upland	Tetraploid	Southern Nebraska 41°	90
Shelter = NY4006	mixed?	Octoploid?	West Virginia 40°	179
Summer	upland	Tetraploid	South Nebraska 41°	114
Sunburst	upland	?	South Dakota 44°	198
Trailblazer	upland	Octoploid	Nebraska 40°	185

(Alderson and Sharp, 1993; Anonymous. 1979; Barker et al., 1988; Barker et al., 1990; Boe and Ross, 1998: George and Reigh, 1987; Gunter et al., 1996; Hopkins et al., 1995; Hopkins et al., 1996; Jung et al., 1990; Newell, 1968; Stout et al., 1988; Vogel et al., 1991; Vogel et al., 1996). A question mark indicates that there are contradictions in the literature.

† Seed weight is expressed as seed weight per 100 seeds in mg. Reported seed weights are those found by the authors in one or two seed samples but should be typical for the variety.

5.4 Variety choice

Winter survival

It is known that varieties that are moved too far north from their origin will fail to mature in fall and have reduced winter survival. This is illustrated in Figure 1 for switchgrass varieties differing in latitude of origin grown in the Netherlands. Southern varieties did not flower in the fall and were still partially green when while northern varieties had flowered and were mature (brown). A frost killed the above ground (green) parts of the southern varieties in November. The failure to winter harden before a killing frost lead to reduced re-growth in spring (Figure 1). The delayed re-growth can then have a negative effect on the yield as discussed below.

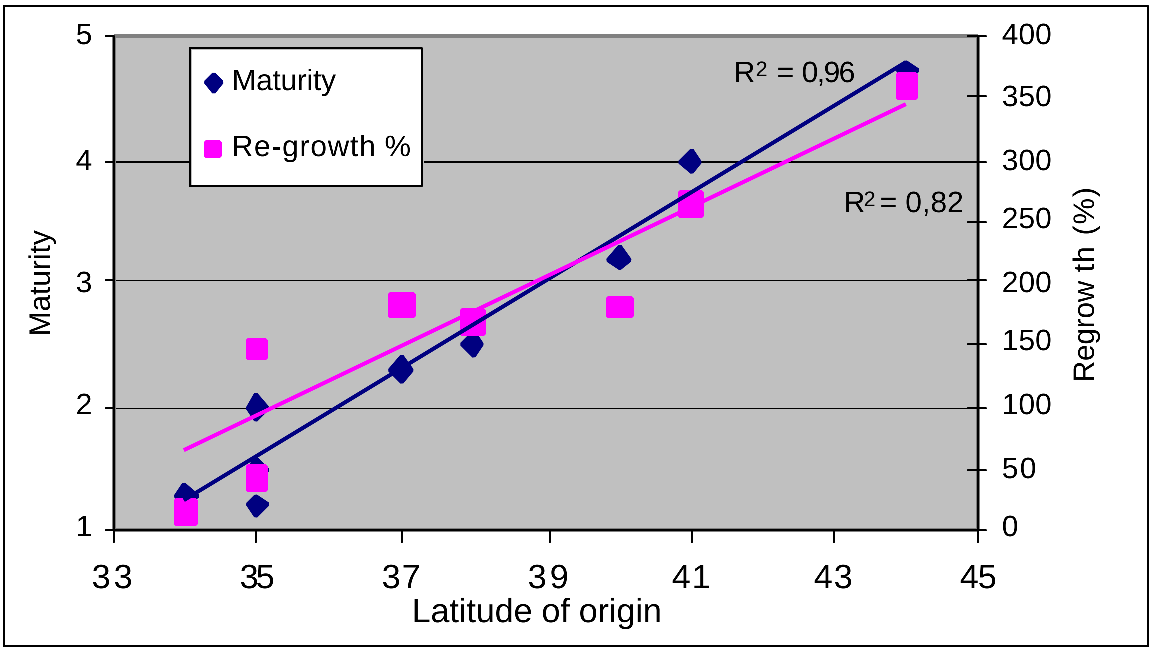

Figure 1. Relationship between latitude of origin of switchgrass varieties and maturity rating in fall and re-growth in early spring. First (establishment) year at Wageningen (NL)

Yield

The most important factor determining area of adaptation of switchgrass varieties is latitude of origin. The plant has a photoperiod response which is modified by growing degree days (Moser and Vogel, 1995). Decreasing day-length will induce flowering in early summer. Other factors determining adaptation are precipitation and humidity. Varieties developed in dry areas will be more susceptible to fungal diseases when grown in humid conditions.

When different varieties are grown at the same site northern ecotypes will remain shorter, flower earlier and mature earlier than southern ecotypes. Also, production of biomass will be considerably less compared to southern types (Jacobson et al., 1984). A clear strong correlation has been found (in Texas, and Canada, N. America) between time to maturity, latitude of origin of the variety and yield (Sanderson et al., 1999, Samson et al., 1997). This effect can also be found in Europe as demonstrated in Figure 2A. Southern varieties matured later and had higher yields than northern varieties.
At northern sites (Figure 2B) intermediate varieties appeared to have highest yields in the second year. The lower yields for the southern varieties at Rothamsted (UK) and Noordoostpolder (NL) can be explained by lower winter survival and re-growth of southern varieties in the first (establishment) and subsequent years. Southern varieties mature too late to winter harden and translocate nutrients before winter sets in, leading to reduced re-growth in spring and lower yields. This is illustrated in Figure 2. (Figure 2B).

Quality

Quality of biomass for energy purposes depends on the type of application. Generally low moisture contents are required to reduce transportation costs and make storage possible. Furthermore low ash and nutrient contents are required when the biomass is used for combustion. K and Cl lower biomass quality by lowering the ash melting point and increasing corrosion problems in combustion systems. Nitrogen content increases NOx emissions.

Southern varieties generally have higher water contents at harvest because they mature later and have thicker stems. This reduces the harvest window and biomass quality (Christian and Elbersen, 1998). This is illustrated in Figure 2C and D, where northern varieties had lower moisture content at harvest both at southern and west European sites.

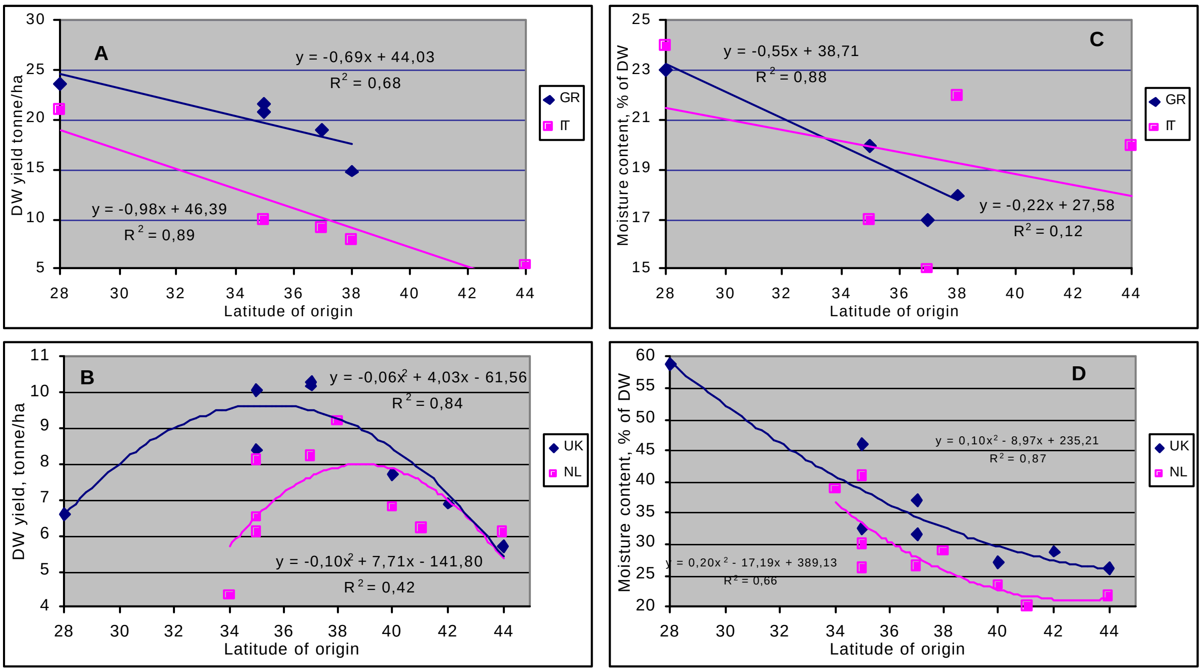

Figure 2. Relationship between latitude of origin of switchgrass varieties and second year biomass yields (A and B) and moisture content of the biomass (C and D). The experimental sites were located at 38 degree north (Aliartos, Greece); 40 degree north (Trisaia, Italy); 52 degree north (Rothamsted, UK) and 52 degree north (Wageningen, the Netherlands). Harvests were made in winter or early spring.

Southern varieties that mature very late in fall will fail to translocate nutrients to the below ground parts before winter sets in. This is illustrated by the results of nutrient analysis in the Netherlands (Table 2) in the second year after establishment.

At a clay and a sandy site in two consecutive years varieties originating at northern latitudes (Forestburg, Summer) consistently had lower Cl and K contents than the southern variety Carthage while the intermediate varieties had intermediate Cl and K contents (Table 2). N and P, nutrients which are not mobilised as easily, were also relatively low in the northern variety Forestburg but here the effects of latitude was less evident, especially in the 2000/2001 season (Table 2). The relationship is also illustrated in Figure 3 where a clear and consistent negative correlation is found between the latitude of origin of a variety and the content of N. P, K and Cl of the biomass for a clay and a sandy site over two years in The Netherlands.

In 2000 heavy lodging of switchgrass, especially at the clay site, impeded trans-location of nutrients to the below ground parts also for northern varieties, which may have reduced the relationship between nutrient content and latitude of origin of a variety. At the clay site much higher ash contents were measured. This is expected as on clay soils silica uptake tends to be higher. This illustrates that apart from latitude of origin also other variables are important in determining biomass quality (and yield).

Thus it is likely that at NW European sites southern varieties contain more nutrients especially K, Cl and to a lesser extent N and P which will reduce biomass quality for energy and fibre applications. At more northern latitudes southern varieties will also require more fertiliser than northern varieties.

Table 2. Ash and nutrient content of switchgrass varieties differing in latitude of origin. The plots were established in 1998 on a clay soil type (Noordoostpolder) and on a sandy soil (Wageningen). The latitude of the two sites is approximately 52 and 53 degree north. Plots were harvested after a killing frost in winter.

1999-2000		Noordoostpolder, clay site					Wageningen, sandy site				
	Latitude	Ash	Cl	N	P	K	Ash	Cl	N	P	K
	°north	% DW	kg/tonne				% DW	kg/tonne			
Forestburg	44	5,83	0,32	4,13	0,52	1,06	1,60	0,41	4,26	0,61	1,36
Summer	41	4,87	0,27	4,06	0,54	1,23	1,80	0,27	4,31	0,58	1,03
CIR	38	5,51	0,97	6,69	0,67	4,38	2,20	1,10	4,56	0,58	2,46
Blackwell	37	5,80	0,86	5,27	0,69	2,93	2,60	0,83	4,66	0,66	2,34
Carthage	35	5,30	1,48	6,56	0,88	5,61	2,60	0,83	5,86	0,75	3,31

2000-2001		Noordoostpolder, clay site					Wageningen, sandy site				
	Latitude	Ash	Cl	N	P	K	Ash	Cl	N	P	K
	°north	% DW	kg/tonne				% DW	kg/tonne			
Forestburg	44	8,90	0,35	7,55	0,88	1,74	2,20	0,23	7,37	0,83	1,40
Summer	41	7,88	0,36	8,73	1,03	2,43	2,20	0,24	7,22	0,81	2,03
CIR	38	8,51	0,59	9,55	1,05	3,47	1,20	0,46	8,05	0,86	2,76
Blackwell	37	10,20	0,51	8,55	1,03	2,61	2,60	0,49	9,11	1,13	2,70
Carthage	35	8,50	0,54	8,83	1,12	3,35	2,00	0,52	7,39	0,99	2,72

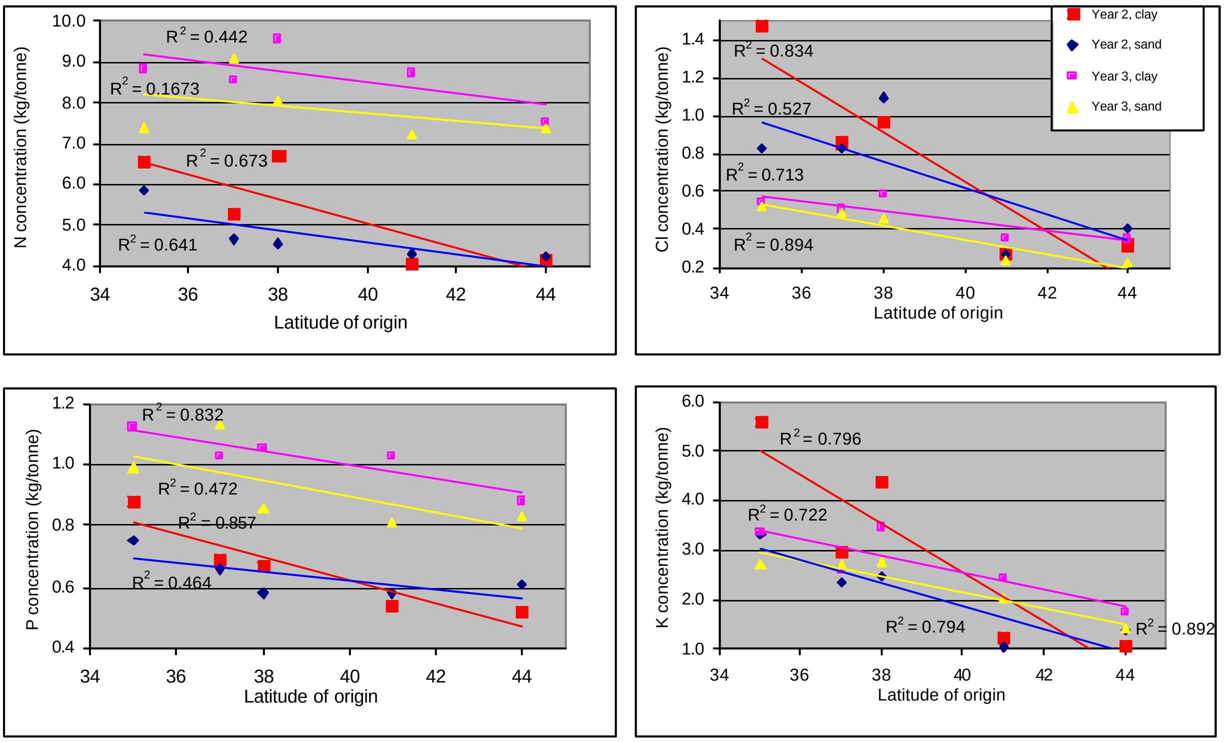

Figure 3. Relationship between the latitude of origin of 5 switchgrass varieties (Forestburg, 44 degree north; Summer, 41 degree north; Cave in Rock 38 degree north; Blackwell 37 degree north; Carthage 35 degree north) and the nutrient content of the harvested biomass over the second (1999) and third (2000) growing season on a clay and a sandy site in The Netherlands.

5.5 Conclusions

It is possible to find switchgrass varieties that are adapted to most regions of Europe. The latitude of origin of a variety is the most important aspect determining the area of adaptation of a variety. Generally the use of varieties originating at southern latitudes can increase DM yields but it will also increase the chance of establishment failures in the first year and a decline in yields over time. Furthermore the quality of the biomass will be reduced (high moisture and nutrient content) if the variety does not mature in the fall. The best variety for a given latitude or geographical area will be a compromise between yield, quality and winter survival. From the current data on switchgrass grown in Europe it appears that switchgrass may be grown further north than in North America.

5.6 Acknowledgements

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6 Switchgrass establishment

6.1 Introduction

Development of effective establishment methods for switchgrass is an important requirement for succesful introduction of switchgrass as a biomass crop in Europe. In the current project experiments were executed to test the effect of a number of important variables on switchgrass crop establishment under European conditions. At experimental sites in Braunschweig Germany and at Trisaia, Italy the effect of drilling date, seedling rate and weed control was followed over two seasons. The results are presented in chapter 6.2.

Other experiments were carried out at Bologna, Italy, to test the effect of seedbed preparation on emergence of switchgrass seedlings. Results can be used to develop methods for establishing switchgrass more cost effectively especially in sloping areas. The results have been published (Monti et al., 2001) and an abstract of the results is presented in chapter 6.3.

6.2 Effects of different seeding rates, drilling dates and weed control on establishment of switchgrass (*Panicum virgatum* L.) varieties in northern Germany and Southern Italy[5].

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Abstract

Establishment of switchgrass, a native species of the North American Great Plains, was evaluated under contrasting climatic conditions in Germany and Italy. The effects of drilling dates, seeding rates and weed control on growth and dry matter production of two contrasting switchgrass varieties was evaluated at two sites in Europe. The varieties were Cave-in-Rock, Alamo and Kanlow, drilling dates were April and June 1999 in Germany and April and May 1999 in Italy. Seeding densities were 200 and 400 pure live seed (PLS)/m^2. Plots had either no weed control or chemical control with the herbicide 2.4-D. The higher seeding rate resulted in greater plant density but did not affect dry matter yield. The early drilling date (April vs June) in Germany significantly increased dry matter yield while the late drilling date in Italy (May vs April) increased yield. Generally northern upland-ecotypes of switchgrass are more adapted to cooler northern climatic conditions. Results show that the lowland-ecotype Kanlow could overwinter and establish near Braunschweig in Germany. Weed control resulted in increased biomass yield in Italy but not in Germany Yield in Italy may have been affected by summer drought as irrigation was necessary in both years. Up to 12-16 t DM/ha were harvested in Germany compared to maximum yield of 8 t/ha in Italy. Biomass yield resulting from the different treatments ranged from 5.09-8.9 tonne DM/ha in 1999 and 10.6- 16.6 in 2000. In Italy, yield ranged from 1.63-15.36 tonne DM/ha.

Keywords: switchgrass, seeding rate, weed control, Europe, drilling date, biomass yield

[5] This chapter is to be submitted for publication.

Introduction

Switchgrass (*Panicum virgatum* L.) is a tall grass species native of the Northern American Great Plains [13]. Switchgrass has been cultivated and investigated in North America. Varieties have been identified that can grow under similar climatic conditions in Europe and the Middle East [8, 9]. Switchgrass can grow to heights of more than 2 m and produce up to 30 t DM/ha [2]. The biomass is suitable for energy production and paper pulp [6].

The wide distribution of switchgrass in different North American climatic regions suggests that there are also varieties to be found that may be productive under European climatic conditions. Switchgrass can be established at low cost using seed [2] and the species requires little input of fertiliser and herbicides once the crop is established. Development of reliable establishment methods is essential for introduction of switchgrass as a biomass crop in Europe. Important factors determining success of establishment are seeding rate and drilling date. These factors have only been investigated in North America [11,12,13]. The North American literature shows different recommendations for drilling date under contrasting climatic conditions [10]. The effect on yield resulting from weed competition has been investigated in America where it was found that weed control is an essential factor during establishment (7). The effect of seeding density, weed control measures and drilling date have not previously been investigated in Europe. In this report the effect of different drilling dates, seeding rates and weed control measures will be presented. Experiments have been conducted at Braunschweig in north Germany under cool climatic conditions and at Trisaia in southern Italy under warm, dry Mediterranean conditions. Here we present the results of experiments conducted over two growing seasons in 1999 and 2000.

Material and Methods

The experiments were located at the Federal Research Centre of Agriculture, Braunschweig in North-west Germany and at the ENEA experimental station at Trisaia, Southern Italy. The soils at Braunschweig and Trisaia are loamy sand and sandy clay respectively. The field trials in Germany were established in 1999 on the 28th April (early date) and 23rd June (late date). In Italy the plots were drilled on 21st April 1999 and 21st May 1999. In both countries the seed rates compared were 200 and 400 pure live seed (PLS)/m^2. The experimental plots have been treated either with no herbicide or with 0.5 kg ai /ha 2-4-D applied in April of each year. The fields were fertilised with 75 kg N/ha. The experimental treatment plot size was 7 m^2. The experimental design at both sites was randomised blocks with three-fold replication. Statistical analysis was carried out using ANOVA of the SAS programme. In Italy irrigation was necessary, during the vegetation period 240 mm and 210 mm water were applied in 1999 and 2000 respectively.

Three switchgrass varieties were used: Cave-in-Rock (CIR, upland/lowland ecotype) in both countries and Kanlow (lowland-ecotype) in Germany and Alamo (lowland-ecotype) in Italy. The seeding rates were for CIR: 1.113 g/m^2 (400 PLS) and 0.556 g/m^2 (200 PLS), for Kanlow: 1.304 g/m^2 (400 PLS) and 0.652 g/m^2 (200 PLS) and for Alamo: 0.562 g/m^2 (400 PLS) and 0.281 g/m^2 (200 PLS).
Crop development and biomass production were recorded during the years 1999 and 2000. The weather details in Germany and Italy during the experiment are presented in Table 1. During 1999 and 2000 very dry weather occurred in both countries. A summer drought in Italy made irrigation necessary.

Table 1. Weather details at the two experimental sites.

Location	Braunschweig, Germany		Trisaia, Italy	
Year	1999	2000	1999	2000
Air-Temperature °C	10,4	10,6	16,6	17,4
Sunshine duration, hr	1730	1569	2807	3028
Precipitation, mm	536	544	176	345
Evaporation, mm	689	637	1477	1623
Difference, mm	-153	-93	-1061	-1068

* Yearly average, all other data calculated as yearly total
** Calculated as sum from January until November

Results

Germany:

Due to the late drilling date (June, 1999) the growth period was quite short in Germany, nevertheless plants established well (Table 2) and reached a height of 122 cm. The crop stand rating was scored once in July 1999 during the vegetation period. There were more gaps present in the stand of Kanlow than in Cave-in-Rock (Table 2). A higher seeding rate also resulted in a higher shoot density. Cave-in-Rock had 407 shoots per m^2 as compared to Kanlow (max. 437) in 1999 and shoot density was also greater in 2000 (Table 2). Maximum shoot density for both varieties was measured in 2000 in plots drilled in June 1999 .

Plant height and shoot density were not affected by weed control measures (herbicide treatment or control, no herbicide). In 2000 switchgrass varieties grew up to 140 to 180 cm, which is taller than in the previous year (Figure 1). Shoot height was greater in the April-sown crop compared to the June-sown and on plots with the lower plant density; Kanlow had the tallest shoots.

Biomass yield was greater in 2000 than 1999 (Table 4). Between 5 and 8.9 t DM/ha were harvested in 1999 compared with 10.6 and 16.6 t in 2000. Significantly lower yield was obtained from June-sown plots. There was no statistically significant difference between low and high seeding rate treatments. In 1999 and 2000 Kanlow was more productive than Cave-in-Rock (CIR) although in 2000 the difference was only on the 200 PLS/m^2 treatment.

Italy:

In the Italian study the variety Kanlow was replaced by Alamo. Shoot density, plant height and crop stand score are presented in Table 3. Shoot density was higher in plots drilled with 400 PLS/m^2 than in plots drilled with 200 PLS/m^2. The highest plant density was measured in Cave-in-Rock (CIR) for 400 PLS/m^2. The shoot density was higher in the May-sown compared to the April-sown treatment. Weeds affected plant growth, particularly during the first year. Weed control with 2.4-D lead to increased plant density in both varieties.

Compared with plant heights in Germany, Cave-in-Rock (CIR) in Italy grew only 110 cm tall in the first year 1999 (Figure 2). Plants grew taller in the late-drilled compared to the early drilled treatment. Alamo was taller than CIR in both 1999 and 2000. In 2000 both the early and late drilled Alamo treatments were taller than the Cave-in-Rock plots (Figure 2). No significant treatment differences were present between the plots that received herbicide compared to the control.

Switchgrass grew very slowly in 1999 and could not compete with the weeds. Yields were very low and are not presented in the tables. During the second year, the highest yields for both drilling dates were obtained from Alamo (Table 5). The yields reached up to 15.4 tonne DM/ha in the herbicide treated Alamo plots. Yields were consistently higher in plots drilled in May 1999 compared to April.

Discussion

Although in Germany frost occurred during winter and the growing period was shorter than in Italy, switchgrass productivity was comparable for both varieties. In both countries higher seeding rates increased shoot density. In Germany this did not result in higher yield while it did increase yields in Italy. A lower plant density and shorter plant height was observed in Italy for Cave-in-Rock.

Yields in Germany were comparable with those in the USA [2]. In Germany Kanlow grew more slowly, had later shoot growth in spring but produced more biomass than Cave-in-Rock. Alamo produced the highest biomass in Italy.

In the first and second year the late (June) drilled treatment showed lower DM yield than the early drilling treatments (April). This was the case for both varieties in Germany. There was very little or no effect of drilling rate on yield. Contrasting results were observed in Italy, where higher yields were obtained on the later seeding dates but again no significant differences were recorded between early and late drilling date treatments. Longer day length together with higher temperatures might have promoted growth in plots drilled in May in southern Italy [4].

A key factor for switchgrass cultivation is the establishment. For most of the varieties and treatments under study establishment was successful although weed competition was observed during the first year. It is recommended to continue the experiments for at least 5-6 years in order to assess yield potential and best adapted switchgrass variety in Germany as well as in Italy.

5. Conclusions

Different drilling densities did not affect dry matter yields also under contrasting climatic conditions in northern Germany and southern Italy. Higher intra-specific competition in plots with high drilling rates might reduce stem weight but needs to be proved in further experiments. Earlier drilling resulted in taller plants and higher yields in northern Germany. In southern Italy the effect the other way round with later established plots doing better than the earlier established plots. Explanations may lie in weed competition in the earlier established plots.

Weed competition occurred especially during the first year in northern Germany but disappeared during the following year. Warmer climatic conditions led to severe weed competition in Italy, which led to low dry matter yield in the first year.

In Italy, switchgrass stand recuperated well in the second season. In the first year establishment was complex and plant growth was affected by summer drought. Under climatic conditions in Italy, switchgrass plants have grown much better for late sowing dates in May compared to earlier dates in April.

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Table 1: Weather conditions at Braunschweig (northern Germany) and Italy in the years 1999 and 2000 (yearly sums and average)

Table 2: Shoot density and plant establishment ratings during the vegetation period in the years 1999 and 2000 for switchgrass varieties Cave-in-Rock (CIR) and Kanlow under 200 or 400 Pure Live Seeds (PLS)/m^2 seeding rates, drilled early (April) or late (June) under no weed control (K) or chemical weed control (C) measures. (Location: FAL, Germany).

	21-7-1999		3-5-2000	21-6-2000
Variety/date	Shoot density tillers / m^2	Establishment rating (1 to 6)	Shoot density tillers / m^2	Establishment rating (1 to 6)
Drilled in April				
CIR 200 K	228	4	1089	5
CIR 200 C	214	5	1096	4
Kanlow 200 K	220	4	1044	4
Kanlow 200 C	170	4	1033	4
CIR 400 K	382	5	1340	5
CIR 400 C	402	5	1399	6
Kanlow 400 K	189	5	938	5
Kanlow 400 C	214	5	1012	5
Drilled in June				
CIR 200 K	218	5	1326	5
CIR 200 C	201	5	1319	6
Kanlow 200 K	271	4	1153	6
Kanlow 200 C	273	4	1078	5
CIR 400 K	294	6	1623	6
CIR 400 C	328	6	1710	5
Kanlow 400 K	433	6	1655	6
Kanlow 400 C	437	6	1456	5

Table 3: Shoot density and plant establishment ratings during the vegetation period in the years 1999 and 2000 for switchgrass varieties under 200 or 400 Pure Live Seeds (PLS)/m² seeding rates, drilled early (21 April 1999) or late (21 May, 1999) under no weed control (K) or chemical weed control (C) measures. (Location: ENEA Trisaia, Italy)

	21-7-1999		21-7-2000	
Variety/date	Shoot density tillers / m^2	Establishment rating (1 to 6)	Shoot density tillers / m^2	Establishment rating (1 to 6)
Drilled in April				
CIR 200 K	246	3	300	4
CIR 200 C	280	3	367	4
Alamo 200 K	242	5	300	3
Alamo 200 C	272	3	467	3
CIR 400 K	344	4	567	4
CIR 400 C	390	3	467	4
Alamo 400 K	260	2	567	3
Alamo 400 C	324	4	500	4
Drilled in May				
CIR 200 K	276	2	333	5
CIR 200 C	360	3	534	5
Alamo 200 K	147	1	534	4
Alamo 200 C	336	4	734	5
CIR 400 K	356	5	433	5
CIR 400 C	456	3	734	5
Alamo 400 K	350	6	567	6
Alamo 400 C	310	3	500	6

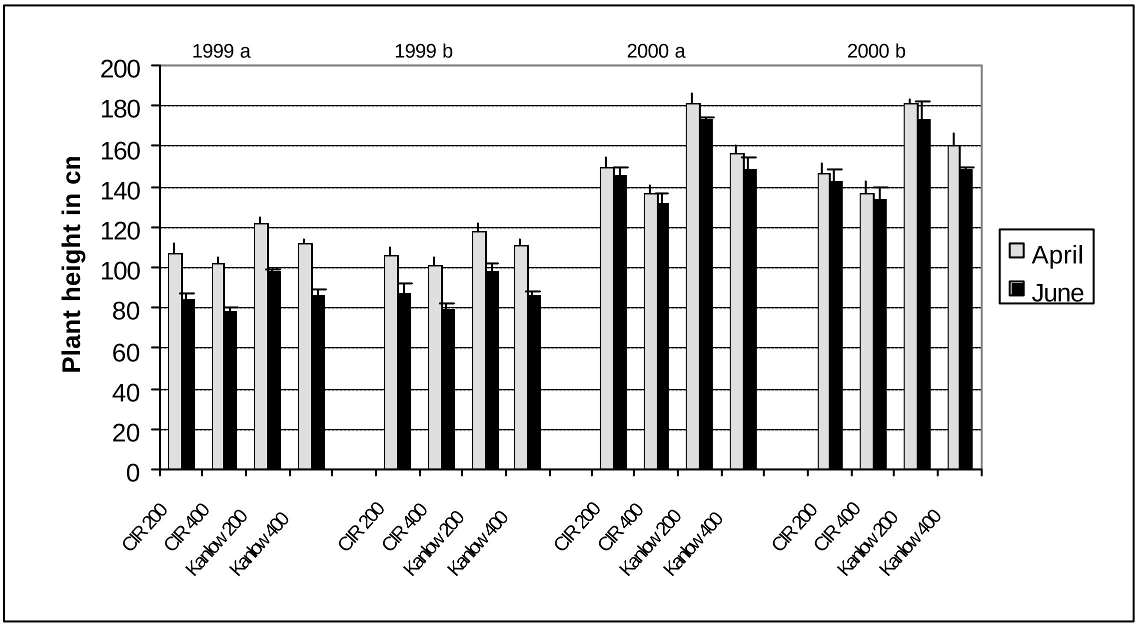

Figure 1: Plant height of switchgrass varieties Cave-in-Rock (CIR) and Kanlow in 1999 and 2000 under 200 or 400 Pure Live Seeds (PLS)/m² seeding rates, drilled early (April) or late (June) under no weed control (a) or chemical weed control (b) measures. (Braunschweig, Germany).

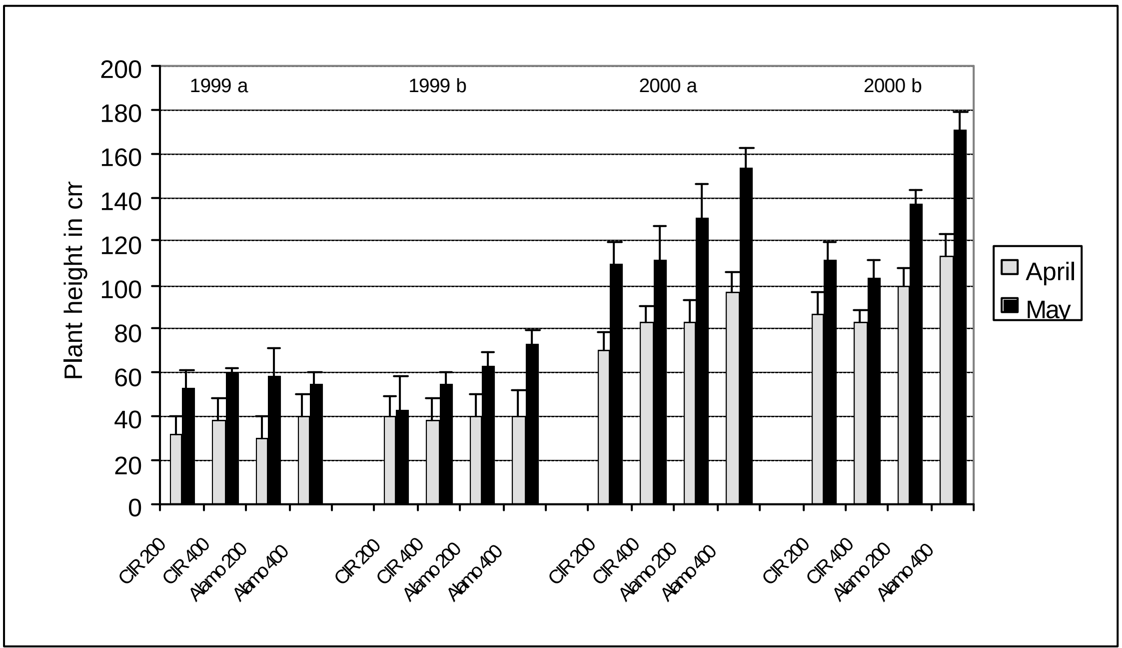

Figure 2: Plant height of switchgrass varieties Cave-in-Rock (CIR) and Alamo in 1999 and 2000 under 200 or 400 Pure Live Seeds (PLS)/m² seeding rates, drilled early (21 April 1999) or late (21 May, 1999) under no weed control (a) or chemical weed control (b) measures. (Trisaia, Italy)

Table 4: Biomass yield in tonne DM/ha calculated from experimental plots of switchgrass varieties in northern Germany at 200 or 400 Pure Live Seeds (PLS)/m² seeding rates, drilled early (28 April 1999) or late (23 June 1999) under chemical weed control or no weed control measures. (mean with standard deviation and LSD for p=0,05%)

Treatment	CIR 200	CIR 400	Kanlow 200	Kanlow 400
1999				
April K	6,9±0,7	6,4±0,6	8,9±1,1 a	8,7±0,1 a
April C	6,5±0,5	6,9±0,5	8,6±0,8 a	8,6±0,4 a
June K	5,1±0,3 b	5,2±0,2 b	6,1±0,3 a b	6,8±0,2 a b
June C	5,2±0,3 b	5,5±0,3 b	5,3±0,3 b	6,8±0,1 a b
LSD 0,05, variety	0,41 a=significant	LSD weed control	no significance	
LSD 0,05, date	0,29 b=significant	LSD density:	no significance	N=48
2000				
April K	15,4±2,9a	16,6±2,3	16,4±1,1	16,4±0,7
April C	13,8±1,0 a	15,6±2,3	16,5±1,5	15,7±0,9
June K	11,8±1,9 b	10,6±0,6 a b	13,0±0,9 b	11,8±1,1 b
June C	11,8±0,8 b	10,7±1,5 a b	12,3±1,2 b	12,7±0,9 b
LSD 0,05, variety	0,78 a=significant	LSD weed control:	No significance	
LSD 0,05, date	0,56 b=significant	LSD density:	No significance	N=48

K = no weed control; C = chemical weed control
Seeding density: 200 or 400 PLS/m²

Table 5: Biomass yield in tonne DM/ha calculated from experimental plots of switchgrass varieties in southern Italy at 200 or 400 Pure Live Seeds (PLS)/m² seeding rates, drilled early (April) or late (June) under chemical weed control or no weed control measures in the year 2000 (mean and standard deviation).

Treatment 2000	CIR 200	CIR 400	Alamo 200	Alamo 400
April K	1,6±0,7	2,8±0,4	2,8±0,4	3,0±0,5
April C	2,4 0,7	2,7±1,0	2,7±0,5	5,9±1,1
May K	3,9±1,3	5,3± ,6	7,4±1,4	10,6±2,4
May C	4,2 ±1,1	5,7±1,3	12,9±1,1	15,4±2,2

K = no weed control; C = chemical weed control
Seeding density: 200 or 400 PLS/m²

6.3 Evaluation of the establishment of lowland and upland switchgrass (*Panicum virgatum* L.) varieties under different tillage and seedbed conditions in northern Italy[6]

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Abstract
Information is needed on potential biomass crops for marginal lands in southern Europe. The objective of this study was to investigate switchgrass establishment in four seedbed preparation treatments (sowing, rolling before sowing, rolling before and after sowing and no till) for two varieties (small and large seed types). A 4x2 split-plot factorial design with four blocks was adopted over a 2 years period. Trials were conducted in Bologna (latitude 44°33'N, longitude 11°21'E, 32 m a.s.l.), in a silt loam soil (Udic Ustochreps fine silty, mixed, mesic). In general, emergence was lower in the autumn trials than in the spring one. Emergence on rolled soil (single and double) was statistically higher than tilled unrolled soil. Cumulative analysis of the two autumn trials including no till showed a significant ($P \leq 0.05$) interaction between treatment and varieties: the large seed variety had a better performance only with no till, particularly in the first year. Overall, if no till was not considered, no significant interactions between variety and tillage treatments were found for final seedling numbers. The statistical analysis on both varieties was therefore combined. Although the double rolled tillage treatment consistently showed a slightly higher average seedling emergence than the single rolled treatment, the final number of emerged seedlings was never significantly different. In all cases, the rolled treatments (single and double) had significantly higher final emergence rates than the treatment with no soil compaction. The average emergence index of unrolled plots was 20 % lower than rolled plots. A function was calculated to predict the seedling numbers at the end of emergence based on the seedling numbers at the beginning of emergence. Generally rolling was needed to obtain best switchgrass performances. In northern Italy both varieties had a good emergence when soil conditions were appropriated..

Keywords: Switchgrass, *Panicum virgatum*, Seedbed preparation, Seedling establishment, Northern Italy.

[6] Monti, A., P. Venturi and H.W. Elbersen (2001) Evaluation of the establishment of lowland and upland switchgrass (*Panicum virgatum* L.) varieties under different tillage and seedbed conditions in northern Italy. Soil & Tillage Research 63 (2001) 75-83.

7 Thermal conversion of switchgrass

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7.1 Switchgrass analysis

A switchgrass sample of variety Alamo originating from the ENEA experiment station in Trisaia, Italy, has been analysed and the results are compared to the results of a switchgrass sample from England and with analysis results from literature. Secondly the composition of switchgrass has been compared to averaged analysis results for *Miscanthus*.
Composition of switchgrass is typical for a biomass that on the average comprises of 50% carbon, 43% oxygen and 6% hydrogen with 1% ash. Switchgrass has however a considerable higher ash content, up to 4%, which can be explained by the higher share of leaves material.
Switchgrass samples from Italy and England are very much the same. Main difference is in the ash melting temperatures, which are 130 to 190 °C higher for the English sample. This can be explained from the higher K content in the Italian sample because K tends to reduce ash melting temperatures.
Comparison with the average values of four *Miscanthus* samples shows that the composition of *Miscanthus* is largely the same as of switchgrass. The four *Miscanthus* samples show a large variation in chlorine content, from 0.5 to 0.03. This spread can be explained from the location where the *Miscanthus* is grown. Areas close to the sea tend to produce *Miscanthus* with higher chlorine contents. The same may be true for switchgrass.
Ash melting temperatures for *Miscanthus* are lower than for switchgrass, but no data on the K content of *Miscanthus* is provided.

7.2 Fouling, slagging and corrosion

Biomass contains inorganic elements which are released from the ash during combustion and deposit on the surfaces of the combustion unit. This is called fouling. Slagging relates to the melting of these deposits, forming a glassy layer. Interaction of the deposits with the metal surfaces can accelerate corrosion, which gradually destroys the metal surface, leading to increased maintenance requirements and reduced service life of the installation.
Deposit formation, which results in slagging, fouling and corrosion, is a complex phenomenon, which involves alkali metal release during combustion, gas phase reactions, transport phenomena, gas and surface temperatures and surface interactions and chemical reactions. In spite of intensive research over the last years, the deposition mechanisms are not yet known in detail. However, there is general agreement on some parts of the mechanism.
Initial mechanism of deposition is condensation of KCl and K_2SO_4, formed by volatile elements such as K, S, and Cl, which vaporise during combustion. This initial layer will melt and become sticky, thus trapping non-volatile elements like Si, Ca and Mg.
K reacts with Si to form alkali silicates, which have significantly reduced melting points. The other elements form eutectics with low melting points, where mixtures with high K concentrations display the lowest melting points. Next to K, Cl is a major factor in deposit formation.
Corrosion of metal surfaces can be accelerated by alkalis and chlorine because the protective oxide layer on the metal can be destroyed.
So the formation of deposits is closely related to corrosion. This means that a decrease in deposit formation will also reduce corrosion problems.
The concentration of K and Cl in switchgrass, 0.21 and 0.23% is in the order of magnitude as for *Miscanthus*, higher than for wood, but lower than for straw or grass. On the basis of this analysis a moderate corrosion behaviour for switchgrass can be expected.

7.3 Corrosion tests

Corrosion tests were conducted in a special test rig of BTG, consisting of an oven in which two metal samples have been exposed to biomass vapors (in this case switchgrass vapors) at high temperatures (from 500 to 850 °C). These samples have been analysed and following conclusions can be drawn.

During combustion of switchgrass high concentrations of potassium and sulfur occur in the gaseous phase and condensate on the colder surfaces. In these areas, characterised by a green/yellow color, much sulfur, oxygen and, to a lesser extend, potassium are present in the metal.
The results also show a clear reduction of the chrome intensity. Because chrome is withdrawn from the inside material, (chrome diffuses to the surface to react with sulfur, space is created for sulfur and oxygen to react inside the material with other metals like molybdene, nickel etc. On the long term this will lead to serious corrosion and reduction in the thickness of the material.
On spots of the material where no yellow/green deposit has settled, the surface and the oxide layer show a lot of metaloxides, like iron oxide and chromium oxide, where chromium oxide forms a closed oxide layer which will protect the metal.
About the consequences of the test results for the practical situation little can be said. The duration of the tests of two weeks is too short to expect serious corrosion. The analyses results indicate a reduction in material thickness of 15 to 26 :m. From previous, long term experiments can be concluded that on spots where sulfidation occurs, on the long run serious corrosion and material reduction will arise.

7.4 Gasification of switchgrass

Gasification is a process in which organic material is converted to a combustible gas, called producer gas. This producer gas mainly consists of H_2, N_2, CH_4, CO and CO_2 .The producer gas than can be used as a fuel to generate electricity, for example by means of a gas engine or gas turbine or generator.
For biomass gasification several technologies can be applied, depending on scale, fuel type, ash content and ash melting behavior. For the gasification of switchgrass , a fluidized bed seems to be the best applicable technology, because it can handle biomass types with a very low bulk density as well as low ash melting temperatures.
The experimental set-up for the gasification experiments consisted of the fluidized bed gasifier with feeding system, gas cleaning and cooling and a gas engine coupled with an electricity generator. To study the gasification behavior of switchgrass, the plant was operated without gas cleaning and gas engine.
The feeding system was calibrated for the use of grinded switchgrass and the gasifier preheated to 650°C. The experiment starts when the air is adjusted to the desired amount of 10 Nm^3/h. Next biomass feed rate is increased and gasification starts.
The amount of gas produced was measured with a gas meter. By means of side stream condensation, the water, tar and dust content were determined. A gas chromatograph was used to determine the gas composition and the tar composition was determined by solid particle analysis (SPA).
Gas production over the experiment was reasonably constant, with 5% H_2, 3% CH_4 and 11% CO as main combustable components. Lower heating value of the gas was 4 MJ/Nm^3. Tar produced mainly consists of light tar components. Ash production was high, meaning that the ash still contains carbon. No ash melting was observed.
Gasification of switchgrass in a fluidized bed is an perfectly viable option. Feeding causes no problems and the producer gas is of good quality. Tar formation is limited to light tars and no ash slagging occurs. The only point of attention is the relatively high amount of carbon in the ash.

7.5 Pyrolysis of switchgrass

Switchgrass was pyrolysed in a 250 kg/h flash pyrolysis plant based on the rotating cone technology. In the rotating cone reactor sand of ca. 550 °C, acting as the heat carrier, and switchgrass are mixed together and flash pyrolysis (instant evaporation) of the switchgrass particles occurs. Pyrolysis of switchgrass yields non-condensable gases, a condensable bio-oil and charcoal as products. Typically in this type of reactor, biomass decomposes into 70 weight % condensable vapors, 15 weight % non-condensable gases and 15 weight % char. The charcoal is fed back to the system and serves as heating fuel, rending the process endothermic.
The switchgrass was crushed in a hammermill with a screen size of 5 mm. Subsequently it was dried to a moisture content of 2% by weight.
A gas chromatograph was used to determine the gas composition. Gas production over the experiment was reasonably constant, with 5% CH_4 and 32% CO as main combustable components. Lower heating value of the gas was 5.9 MJ/kg.
The bio oil was combusted in the BTG combustion rig. In this rig air atomization nozzles are used. Secondary air is injected around the nozzle. The unit is preheated to 800°C by means of a propane flame.

At 800 °C the propane is slowly replaced by bio-oil. Temperature profiles and emissions are monitored during the experiment.
Switchgrass is a suitable feedstock for pyrolysis oil. A stable oil is formed and can be used in oil burners. Emissions are comparable to emissions from diesel combustion. An oilyield is obtained of 64wt.% of the original feedstock. The analysis of the pyrolysis gases shows a combustible gas with a LHV of 5.9 MJ/kg, which, after removing the aerosols, can be used in, for example, a gas engine.

7.6 The combustion of switchgrass

The combustion in a high temperature furnace environment has been investigated.
When combusting switchgrass the conversion process consists of two phases, first a flaming pyrolysis phase in which rapid devolatization of the switchgrass occurs, and a slow burn-out phase. This burn-out time depends on particle size and geometry and proper designed combustors take the slow char burn-out phase into account.
The experimental setup consists of a stainless steel tube, which has an opening to insert a switchgrass particle. Air can be blown into the pipe at any desired velocity. Prior to each experiment the tube is heated to a stationary temperature by means of a large electrical current. Temperature is monitored by a thermocouple. When a switchgrass particle is inserted in the hot zone, the particle pyrolyses with the emission of flaming volatiles in 1 to 2 seconds. There after the slower char burn-out follows, which takes about 5 to 10 seconds. The complete cycle is recorded on video, so exact conversion times can be determined by detailed inspection of the videotape.
Experiments have been conducted on switchgrass particles with a well defined geometry (3*5*0.8 mm) and on a random sample of milled particles.
Increased air velocity leads to a smaller char burn-out time and less scatter of the experimental outcome. Char combustion time varies between 2 and 7 seconds so a properly designed furnace for the combustion of this type of switchgrass particles (with a flake thickness of 0.6 mm) must have a minimum gas residence time of 10 seconds. For existing boilers, with residence times of less than 3 seconds, the flake like switchgrass particles must be milled to 0.3 mm thickness.
In case switchgrass is milled in a hammer mill to needle like particles with a diameter not larger than 0.5 mm, the conversion time will be less than 3 seconds. These particles can be co-fired in pulverized coal combustors, CFB combustors or entrained flow combustors.
Melting and sintering of the ash has been visually observed at temperatures higher than 1000 °C, so slagging combustion of switchgrass is to be expected.

8 Non-energy uses of switchgrass

8.1 Introduction

Switchgrass is a C4 grass native to the North American Tall grass prairies. It was first collected and utilised for erosion control in the 1930’s. For this purpose it is still being used. Other uses include as a fodder crop during hot and dry summer periods. In the last 15r years switchgrass has been developed for energy (power) and ethanol production mainly in the USA and Canada. In more recent years switchgrass has also been evaluated for paper pulp production, fibreboard and as a reinforcing fibre for composite materials where it may replace fibreglass.

Thermal conversion of switchgrass is presented in the previous chapter. In this chapter we will present short studies to establish the suitability of switchgrass as a feedstock for:
- Paper pulp production (Chapter 8.2)
- Fibre reinforced composites (Chapter 8.3)
- Production of ethanol through lignocellulose to ethanol processes (Chapter 8.4)

8.2 Switchgrass as a raw material for paper pulp production

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Introduction

Although non-wood fibres have been used for papermaking during two millennia, the use of non-wood fibres is limited to about 9% of the world pulp production. China and India are the most important users of non-wood fibres in pulp and paper production. There is an increasing interest in non-wood fibres as a source for pulp and paper production as a result of the environmental problems that arise due to increasing harvesting from wood.
A part of the non-wood fibres exists of long fibres that can be used in specialities like cigarette-, bible-, teabag- and security paper. The bast fibres of hemp and flax and abaca fibres which are longer than softwood are used for this type of specialities.
The main part of non-wood fibre pulp is produced from short fibre sources like straw and bagasse. These pulps are comparable with hardwood pulps that are normally used in printing and writing papers. Short fibres are mainly used to give good surface properties or stiffness to paper and board. The quality of short-fibre pulp is better defined by the number of fibres per weight, fibre stiffness and optical properties, than by strength properties.

Switchgrass is one of the non-wood short fibre sources that have been studied recently for application in paper (Girouard, and Samson, 2000; Goel, et al., 1998; de Jong et al., 1998; Law et al., 2001; Madakadze et al., 1999; Radiotis et al., 1999; Ruzinsky and Kockta, 2000). Especially in Canada this crop is seen as an alternative for hardwood pulps. Compared to aspen the number of fibrous elements smaller than 0.2 mm is high, but the length-weighted average of about 1-mm is comparable (Law et al., 2001).

Chemical pulping

Several authors describe the quality of switchgrass pulp made with different pulping processes. These processes can be separated in low yield chemical processes and high yield mechanical processes. Table 1 gives an overview of their results regarding to yield, optical and strength properties after pulping with different chemical process. As paper properties are depending on the freeness, they should be compared at the same freeness levels. Most of the strength properties are somewhat lower than those of typical birch or eucalypt pulp, but if switchgrass pulp is used in printing or writing papers this is not a disadvantage.
Remarkable is the high bulk of the switchgrass pulp, which makes it profitable to add switchgrass pulp in pulp mixtures for high bulk printing and writing papers. In a total chlorine free process (TCF) switchgrass is

easy to bleach to high brightness levels (Radiotis, et al., 1999). The yield is in the same order of that of chemical pulps of hardwood.

One of the disadvantages of chemical pulping of non-wood fibres is that they can contain high concentrations ash and/or silica. Well known is the high concentration of ash in cereal straws and the extreme ash content of 18% in rice-straw. Silica causes wearing- and scaling problems in the chemical recovery. Law et al. (2001) report an ash content of about 5% for switchgrass, but Samson and Mehdi (1998) report a much lower concentration of 1.7%. In the current project ash contents of 1.8, 1.9 and 4.4% are reported, depending on the soil type and other condictions. So ash content of switchgrass is low compared to other non-wood fibres, nevertheless wood has normally an ash content below 1%. The ash content must be kept as low as possible by choosing the right soil and preventing that adhering soil is harvested with the grass. Because leaves will fall off, over-wintering is also an expedient that can lower the ash content (Law et al., 2001). It can also raise the average fibre length (Radiotis, et al., 1999) and improve the bleachability (Goel, et al., 2000). The yield will be lower, but the quality of the fibres will improve. Improvements are also possible by using refining methods that remove part of the leaf and node fraction.

Mechanical pulping

Table 2 gives an overview of the different mechanical pulping processes applied to switchgrass and the comparison with aspen APMP pulp, which is the most common hardwood mechanical pulp.
The strength properties of the switchgrass pulps are at the lower site of the aspen pulps.
Except for the tear-index the Alkaline Peroxide Extrusion Pulp of Switchgrass distinguishes itself from the other switchgrass mechanical pulps by its higher strength properties. As with chemical pulps, the bulk of switchgrass pulp is higher than the bulk of hardwood pulps. The mechanical pulps described by Ruzinsky and Kokta (2000) did not undergo a bleaching step. The bleaching of the extrusion pulp was integrated in the process. The brightness was low compared to aspen APMP pulps, but optimisation of the process is still possible by adjusting the Alkaline and Peroxide concentrations, the consistency and incorporation of a washing/pre-treatment stage.
The opacity of the AP extrusion pulp is low compared to the optimal bleached aspen pulp.
Mechanical pulp from switchgrass can replace a part of hardwood mechanical pulps in printing papers if brightness and opacity can be improved. The bulk of the papers will be increased. The yield is low compared to mechanical wood pulps that normally is in the range of 85-95%.

The energy needed to produce mechanical pulps forms a substantial part of the costs of a mechanical pulp. A commercial mechanical pulp normally requires 1200-1800 kWh/ton. The energy needed for an AP extrusion pulp of switchgrass is only 400 kWh/ton.
Ruzinsky and Kokta (2000) report that switchgrass needs half to three quarters less energy for high yield pulping of aspen. So regarding the energy costs the production a mechanical pulp of switchgrass is much cheaper than of a hardwood mechanical pulp.

Addition of switchgrass pulps to pulp mixtures for printing and writing papers is profitable. It will give a higher bulk and lower energy costs in mechanical pulping. Data with respect to printability are not yet available. Further research in that field is necessary.

Other aspects

Studies show that switchgrass is comparatively inexpensive to produce. In the current study the price of switchgrass biomass appears to be favourable compared to other perennial grasses. Economic studies (Fox et al., 1999) indicate that switchgrass should an attractive crop especially on marginal soils that have restricted uses because of low fertility, erosion, or for example strict environmental controls switchgrass may be an attractive crop for paper pulp production.

Conclusions

Switchgrass can replace a part of the hardwood pulps in printing and writing papers. Due to its high bulk it will especially be suitable for bulky printing papers.

Mechanical pulping of switchgrass needs far less energy than mechanical pulping of aspen or other woods. The high productivity under low input conditions results in low cost per tonne of biomass making switchgrass a potentially cost effective replacement for hardwood pulps in printing and other paper types.

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Table 1: Chemical pulps from switchgrass.

		Switchgrass Kraft	Switchgrass Soda-AQ	Switchgrass Kraft TCF (OZEQPo)	Switchgrass Kraft	Switchgrass soda	Switchgrass Sulphite *	Birch Kraft	Birch Kraft	Eucalypt Kraft	Eucalypt Kraft
Yield	(%)	50	48	45	50	44	60-80				
CSF	(ml)	417	289	310	407	100	100	362	320-450**	290-420**	320-450**
°SR								27.1	25	28	25
Bulk	(cm^3/g)	2.1	1.9	1.5	2.1		4.5-3.6	1.2	1.4	1.3	1.7
Tensile index				61.8	74.9	87	22-36	74			
Breaking length	(km)	6.9	8.3	6.3	7.7	8.9		7.5	7.0	6.5	6.2
Stretch	(%)	1.6	1.8	3.1	2.0			3.9			
Burst index	($kPa\ m^2/g$)	3.6	4.5	3.6	4.2	5.6	0.8-2.2	4.9		5.1	
Tear index	($mN\ m^2/g$)	5.2	5.1	4.7	6.7	8.5	4.5-6.8	7.9		8.1	
Brightness	(%)			87.2	29.3	30	30-40	84.1		81.8	
Opacity	(%)				97.7		92-98	71		75.6	
Source		Goel, et al., 2000	Goel, et al., 2000	Radiotis et al., 1999	Madakadze,et al., 1999	Law, et al., 2001	Law, et al., 2002	ATO result	Rydholm, 1985	ATO result	Rydholm, 1985

* production of high yield chemical pulps with different concentrations of different carbonates
** interconversion from Schopper-Riegler to Canadian Standard Freeness according to Tappi TIP 0809-01

Table 2: Mechanical pulps from switchgrass

		Switchgrass AP Extrusion	Switchgrass CTMP	Switchgrass CMP	Switchgrass SEP	Aspen APMP	Aspen* APMP	Aspen* APMP
Yield	(%)	70-80	79	68	66			
CSF	(ml)	170-260**	100	100	100	213	200-290**	170-260**
^{o}SR		42					38	42
Bulk	(cm^3/g)	1.8	4.3	4.1	3.5	2.47	1.66	1.33
Tensile index								
Breaking length	(km)	5.1	2.3	3.3	3.5	3.1	3.6	6.1
Stretch	(%)							
Burst index	(kPa m^2/g)	3.1	0.8	1.3	1.6	1.1	2.3	3.5
Tear index	(mN m^2/g)	3.4	4.5	6.5	6.5		2.8	4.7
Brightness	(%)	52.2	38	26	31	70.8	82.9	81.8
Opacity	(%)	72.5	99	97	96	87.6	77	74
Porosity	(ml/min)	417	1300	230	220		1890	140
Source		de Jong, et al., 1998	Ruzinsky, 2000	Ruzinsky, 2000	Ruzinsky, 2000	Xu E.C., 2001	de Jong, et al., 1998	ATO-result

* Two different pulps
** interconversion from Schopper-Riegler to Canadian Standard Freeness acoording to Tappi TIP 0809-01

8.3 Switchgrass (*Panicum virgatum* L.) as a reinforcing fibre in polypropylene composites

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A study on the suitability of switchgrass as a stiffening and reinforcing agent in polypropylene (PP) composites was executed. The results have been presented in a paper that has been submitted for publication in the Journal of Applied Polymer Science[7].

Abstract

In this study the switchgrass (*Panicum virgatum* L.), a biomass crop being developed in North America and Europe, was tested as a stiffening and reinforcing agent in polypropylene (PP) composites with and without maleic anhydride grafted PP (MAPP) as a compatibilizer and to evaluate the effect of pulping and different sources of switchgrass on composite characteristics. The refiner pulping yield for two switchgrass varieties was estimated between 70-80%. The addition of 30% (by weight) switchgrass pulp resulted in an increase of the flexural modulus by a factor of about 2.5 compared to pure polypropylene (Table 3). Which was only slightly lower than values found for jute and flax. The flexural strength of PP composites reinforced with pulped switchgrass and MAPP was almost doubled compared to pure PP and approached values found for jute and flax. The compatibilising effect of MAPP has been visualised by micrographs. The good mechanical properties are achieved despite the severe fibre length reduction as a result of thermoplastic compounding which is shown by fibber length analysis. The impact strength of switchgrass/PP composites was much lower than for pure PP. The use of different switchgrass varieties and harvesting time had a minor to no effect on the mechanical performance of the respective composites. The chemical composition of different varieties was fairly constant. The low price and the relatively good mechanical characteristics should make switchgrass an attractive fibber for filling and stiffening in thermoplastic composites. Further improvement of composite mechanical properties by improved pulping should be possible.

Table 3. Flexural and Charpy impact properties of switchgrass fibber reinforced PP and PP/MAPP composites.

Fibre [a]	MAPP	Flexural modulus [b]	Flexural strength	Strain	Charpy unnotched impact strength
		---------- Mpa	----------	---- % ----	---- kJ m^{-2} ----
-	No	1210 ±74	42.6 ±1.5	6.9 ±0.2	51.8 ±12.5
-	Yes	1384 ±43	45.9 ±0.6	6.7 ±0.2	93.2 ±8.2
30% A	No	2764 ±105	47.0 ±0.6	3.6 ±0.1	7.0 ±0.9
30% B	No	2718 ±44	48.8 ±0.8	3.7 ±0.1	7.0 ±1.8
30% pulped A	No	2841 ±42	47.5 ±0.6	3.1 ±0.2	9.5 ±1.4
30% pulped B	No	2900 ±203	48.2 ±0.5	3.0 ±0.1	10.0 ±0.7
30% A	Yes	2721 ±159	56.6 ±1.1	3.5 ±0.1	8.3 ±1.1
30% B	Yes	2672 ±101	58.7 ±0.6	3.7 ±0.2	8.1 ±1.2
30% C	Yes	2650 ±126	54.1 ±0.9	3.4 ±0.2	7.6 ±1.5
30% D	Yes	2795 ±88	58.6 ±1.2	3.4 ±0.2	8.3 ±1.4
30% pulped A	Yes	3003 ±58	69.6 ±0.5	4.1 ±0.2	15.1 ±1.3
30% pulped B	Yes	3147 ±81	70.7 ±0.5	4.1 ±0.2	16.9 ±1.3
30% jute [c]	Yes	3500-3900	64-77	4.5	25
30% flax [c]	Yes	3500	76	4.5	25

[a] A = Cave-in-Rock switchgrass, harvested in spring Canada; B = Cave-in-Rock switchgrass, harvested in fall in Canada; C = Kanlow switchgrass, harvested in winter at Rothamsted; D = Cave-in-Rock switchgrass, harvested in winter at Rothamsted. [b] Values are ± standard deviation.[c] Data obtained during separate research programs at ATO. These data are included for comparison reasons only.

[7] Oever, M.J.A. van den, H.W. Elbersen, E.R.P. Keijsers, R.J.A. Gosselink and B. de Klerk-Engels. 2002. Switchgrass (*Panicum virgatum* L.) as a reinforcing fibre in polypropylene composites. Submitted for publication.

8.4 Estimate of the potential production of ethanol through a lignocellulose to ethanol processes based on chemical composition of switchgrass samples.

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In Table 4 the chemical composition of switchgrass is presented. From this we can make an estimate of the potential ethanol production which can be produced through lignocellulose to ethanol processes.

Table 4. Chemical composition of untreated and pulped switchgrass samples from different sources. Kanlow and Cave-in-Rock produced on a sandy site in Wageningen in the second growing season and harvested in winter.

	Kanlow	Cave-in-Rock	Pulped Cave-in-Rock	Radiotis [a]	Madakadze [a]
Ash	1.9	1.8	2.6	1.5	4.8
Extractives	10.4	9.5	- [b]	1.6 [c]	6.9 [d]
Lignin	18.9	19.5	22.5	21.8	23.9
Cellulose	30.5	28.8	33.6	43.4 [e]	43.4 [e]
Hemi-cellulose	30.4	31.2	31.5	35.9	30.5
Pectin	1.4	1.3	1.7	-	-

[a] Literature references: Radiotis, T., Li, J.,Goel K.and Eisner, R. Fiber characteristics, pulpabilty, and bleachability studies of switchgrass. TAPPI Journal 1999, 82, 100-105; Madakadze, I.C. Physiology, productivity and utilization of warm season (C4) grasses in a short growing season area. PhD thesis, McGill University, Montreal, Quebec, Canada, 1997.
[b] Pulp characterized without prior extraction.
[c] Alcohol/benzene extractives.
[d] Cold water, hot water and acetone extractives.
[e] Alpha-cellulose.

A calculation can be made of the potential ethanol production by adding up all the fermentable components and assuming that:

- Holocellulose (cellulose + hemi-cellulose) + pectin has a yield of 0.80 * 1.1 * 0.47 = 0,41
- Conversion of starch to sugars and fermentation has a yield of 1.1*0,47 =0,52
- Fermentation of sugars has a yield of 0.47

This gives an ethanol yield of 262 kg ethanol/tonne dry matter for second year winter harvested Kanlow and Cave-in-Rock samples grown at a sandy site in Wageningen. This yield is comparable to the theoretical ethanol yield from hard wood like willow.

9 Economic and environmental evaluation of switchgrass production and utilisation.

9.1 Introduction

The economic and environmental evaluation of switchgrass will be based on three years of data. Since switchgrass is a perennial crop with a cycle of some 15 years extrapolations and assumptions have been necessary for the economic and environmental analysis. In Chapter 9.1 the economic and environmental analysis of switchgrass cultivation are presented. In chapter 9.3 the economic analysis of switchgrass utilisation for thermal conversion is discussed.

9.2 Cost price calculation of switchgrass

Introduction

Switchgrass has been evaluated as an alternative energy crop in Europe. Research in this area includes investigation of the cost price and yield with regard to switchgrass cultivation. In our case the cost price and yield of switchgrass was investigated for a period of 15 years based on available data or extrapolation of data. The resulting switchgrass cost price (price per tonne DM) was compared to the cost price for *Miscanthus* estimated in other studies.

Current studies show that switchgrass can be cultivated in different regions of Europe. In each region or country the yield and input parameters and therefore the cost price will differ. The inputs and associated costs were estimated individually for the 5 countries participating in the current EU switchgrass project. The participating countries are Italy, Greece, Germany, the Netherlands and the United Kingdom. The inputs, yields and cost price were calculated based on expected local farmer conditions. It should be taken into account that only 3 years of data are currently available for switchgrass in the current project therefore many parameters have been extrapolated from current data and literature.

Available cost information

In general the information provided by the five different countries was similar. Total costs were separated in direct costs (consumable goods) and labour / machine costs, both specified as costs in EURO’s per hectare (EURO / ha). Direct costs are costs for consumable goods like seeds, herbicides, fertilisers, agrochemicals and pesticides. Labour and machine costs don’t have the same meaning for all countries. Labour costs are for example explicitly mentioned in the German and Dutch data. For all other countries the labour costs are integrated in the costs for different activities. In Italian, Greek and UK data spraying costs are for example total costs that are required for carrying out the specific activity. Spraying costs on the German and Dutch cost specification are the costs to use machines. The labour costs are not ascribed to the activity spraying, but included in the total labour costs. Examples of labour and machine costs are costs for ploughing, using the power harrow, rotary cultivating, drilling, rolling, spraying, fertilising, irrigating, mowing, baling and transporting. The costs of land use are not taken into account, because the crops can be produced on non-productive land (that is polluted or that has other restrictions on use), where the costs of land use are assumed to be zero. Another difference is the way different countries calculated their costs. In all cases estimates were made of the required inputs under practical farming conditions and the current costs of these inputs in the respective countries. Differences in estimates of the required input and differences in the cost of these inputs can account for differences between countries. Some countries used the market prices they paid for products and services to grow switchgrass if these data were not available standardised prices or estimates were used.

Method of calculation

Two different methods are used to calculate the cost price of switchgrass. The first method obtains the total costs per tonne of dry matter (DM) by dividing the total costs (EURO / ha) by the total yield (tonne / ha). This method doesn't take into account that costs are made in different years. Because of inflation and the opportunity cost of money, the money spent in year 1 is worth more than money spent in year 15. The second method, that uses the Net Present Value (NPV) of the total costs, takes this into account.

If spending patterns are the same for all different countries, that means the distribution of the costs over the years is similar for all countries and consequently the results of both methods are similar. In our case the spending patterns are quite different. For example the start up costs for Greece are relatively high compared to the amount of money spent by Greece and the UK in all other years and to the amount spent by other countries in the first year. Greece and the UK also have relatively high start up costs compared to the costs in other years, but for Germany and the Netherlands the costs in the first year are similar to the costs in other years. Another difference in the spending patterns for different countries is that in some countries 'expensive' fertilisers are applied in some years.

Results

The total costs are separated in labour & machine costs and costs for consumable goods. Figure 1 shows the total costs over 15 years for the 5 European countries further specified as indicated above without taking the corresponding yield into account.

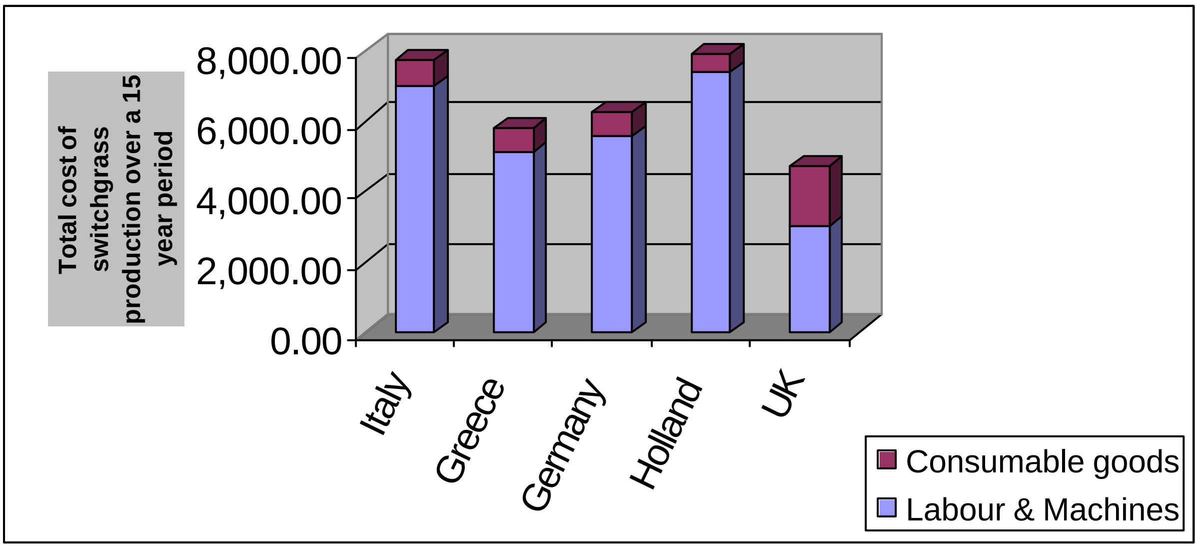

Figure 1: Total estimated costs over 15 years for switchgrass cultivation, in Euro per ha for 5 different countries in Europe.

In most countries the labour and machine costs are high compared to the costs for consumable goods, this agrees with the low input requirements for switchgrass (establishment by seed, low nutrient use and low pesticide use). Labour and machine costs are the highest in the Netherlands. This is explained by the fact that farms are relatively small and the labour costs per hour are very high. The size of German farms is comparable to Dutch farms, but labour costs per hour are lower. The total cost specification in the UK is different from the other countries. A relatively higher amount is spent on consumable goods. Farms in the UK are fairly large, labour and machine costs are low, and the price of (consumable) goods is high. Overall the costs in the UK are relatively low compared to all other countries. Greek labour is much cheaper than Italian labour, so the costs of different activities (labour and machine costs) are lower.

To be able to compare the costs of producing switchgrass for different countries the yield has to be taken into account. Figure 2 shows the estimated yield for all countries over 15 years.

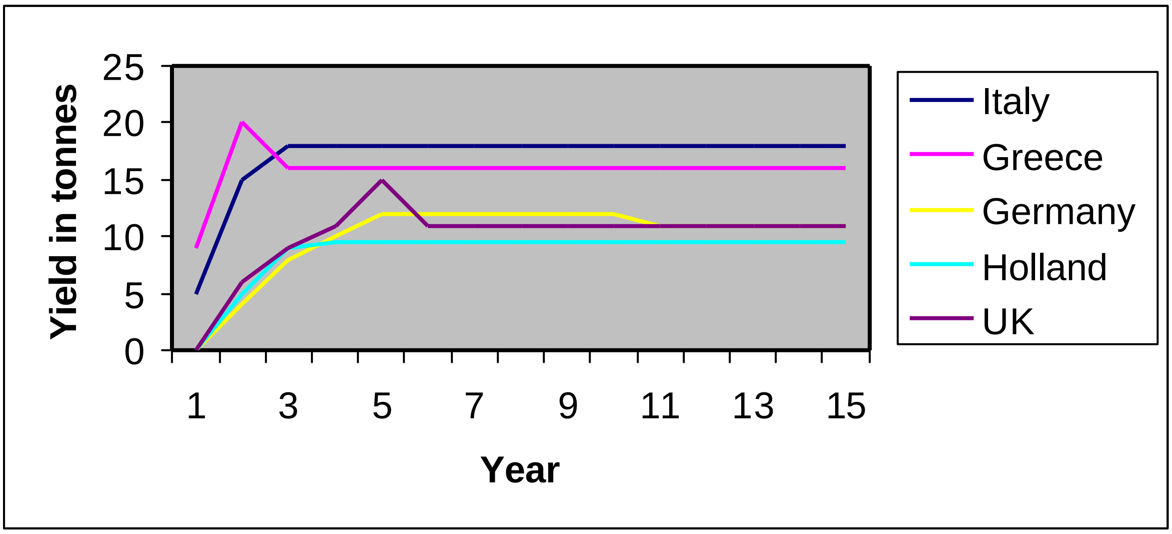

Figure 2: Estimated (extrapolated) yields over 15 years, in tonnes DM per ha per year for 5 countries in Europe.

Overall the expected yields are highest in Southern European countries like Greece and Italy. The weather conditions in these areas are more favourable (longer growing season) than the conditions in Northern European countries like Germany, the Netherlands and the UK. For all Northern European countries the yield in the first year is low and probably not economical to harvest. In Greece and Italy in the first year economical yields are obtained. For Greece and the UK there is a peak in the yield at the beginning of the 15-year growing cycle. This is explained by the fact that for the first years actual data are given and for following years estimates are presented. For both Germany and Holland relatively lower yields are estimated than in the UK. The yield estimates presented here should be seen as preliminary. More accurate estimates can only be obtained form large experimental fields over a larger time frame (>10 years). Furthermore much optimisation of agronomic parameters is possible to optimise yields.

The following table reflects the cost prizes of switchgrass for all five countries calculated in two different ways. Both total costs and total yields are incorporated in the calculations. The first method divides the total costs by the total yield. The second method divides the NPV of the total costs by the total yield. The interest rate was set to 4.93% [8].

Table 1: cost price, in Euro per tonne DM

Country	Cost price (in Euros) per tonne (DM)	
	Method 1	Method 2 (NPV)
Greece	24	18
Italy	30	23
United Kingdom	31	23
Germany	42	31
Netherlands	62	45

Results for both calculation methods are similar because differences between cost prices in different countries are not substantial. Except for the difference between the UK and Italy. The production in Italy is a bit cheaper given method 1 and the results for both countries are the same given method 2. Greece is the cheapest producer of switchgrass, followed by Italy, the UK, Germany and the Netherlands. The Netherlands is by far the most expensive producer. Whilst the UK produces at the lowest costs, the

[8] Interest rate 15 years, NL, 8-11-2001

production level is lower than the yield in Italy and Greece. This results in a lower total cost price for Greece and Italy. Although the cost price in Italy and the UK don’t differ much.

The cost prices for switchgrass for the different countries mentioned above vary between 24 and 62 Euro per tonne DM. The most likely production costs for *Miscanthus* vary between 35 and 105 Euro per tonne DM for different EU countries (Walsh et al. 1997). The break even costs (worst case) for the Netherlands, without including any special incentives or subsidies, have been estimated between 82.78 and 187.86 Euro per tonne DM. In general environmental parameters that affect *Miscanthus* are similar to those mentioned for switchgrass. With *Miscanthus* requiring more input in establishment than switchgrass because *Miscanthus* is planted by rhizomes and switchgrass by seed. In comparison to *Miscanthus*, switchgrass seems cheaper to produce. But the cost prices are not comparable because of the differences in underlying assumptions. In each cost price calculation different cultivation procedure and combination of consumable goods are assumed. Another difference in the underlying assumptions is that the costs of land use are not taken into account in the cost price calculations for switchgrass, whilst these prices are included in the cost price of *Miscanthus*. The costs of land use will be high for The Netherlands for example, and can be reduced by using non-productive land (that is polluted or that has other restrictions on use). Because the costs of land use depend on the basic assumptions about the type of land and the area used, and also heavily differs form site to site, no assumptions can be made on the costs of land use in order to make a comparison. In order to make better comparisons in the future there is need for scaling up production field trials to determine actual commercial biomass yields and costs for switchgrass and other perennial grasses like *Miscanthus*.

Environmental effects

In this paragraph the environmental effects of growing switchgrass and *Miscanthus* will be examined. In order to do this the performance of the biomass crops on four different aspects: fertilisation, energy, irrigation and weed and pest control will be considered. Available data for switchgrass about the costs of irrigation, fertilisation, energy-use and weed and pest control in five European countries have been used in order to measure the performance of switchgrass for these aspects. Comparable information is not always available for all five countries for *Miscanthus*. The disadvantage of using costs as a measure of performance is that it is not known if high costs are caused by high prices of the consumable goods or the high application costs or the high amounts needed. When information about amounts is not available, the costs have been used as an alternative. The available information is compared with literature about the environmental performance of the two biomass crops. Table 2 shows the different costs on the aspects mentioned above for switchgrass. Information about energy use is not available and irrigation didn’t take place in Northern European countries. Comparable information for *Miscanthus* is not available.

Table 2: Estimated cost of different inputs for switchgrass, in Euro per tonne DM, for 5 different countries in Europe.

<table>
<tr><th></th><th>Fertilisation</th><th>Weed and pest control</th><th>Irrigation</th></tr>
<tr><td>Italy</td><td>2,39</td><td>0,12</td><td>10,67</td></tr>
<tr><td>Greece</td><td>2,49</td><td>0,09</td><td>6,32</td></tr>
<tr><td>Germany</td><td>4,16</td><td>0,20</td><td>0</td></tr>
<tr><td>Netherlands</td><td>3,00</td><td>0,40</td><td>0</td></tr>
<tr><td>United Kingdom</td><td colspan="2">9,60</td><td>0</td></tr>
</table>

Fertilisation

The costs of fertilisation for switchgrass range between 2,74 in Italy and 9,67 Euro per tonne DM in the Netherlands. It is not clear if higher costs of fertilisation in Northern European countries are either caused by the amounts applied or the costs for applying them. Fertilisers are applied each year in all countries except for the United Kingdom. In the UK fertilisers are only applied in year 5, 10 and 15. For Greece data on fertilising *Miscanthus* are also available. In comparison to switchgrass the cost per tonne DM for fertilisation are higher for *Miscanthus*. The same amount of Nitrogen is applied, but costs for basic fertiliser that is only applied the first year are higher for *Miscanthus*. The costs in EURO per tonne DM are 4,27 and 3,97 for *Miscanthus* and switchgrass respectively.

Each of the crops will have different management regimes. The management regimes in different environments will also vary. The application of different fertilisers based on Christian and Riche (1999) is as follows: *Miscanthus* needs a yearly application of N, P_2O_5 and K_2O in the proportion 0:0:72 kg per ha. Furthermore it needs the fertilisers described above in the proportion 0:32:0 kg per ha every five years. switchgrass only needs the application of N, P_2O_5 and K_2O every five years in the proportion 0:28:78. Overall more fertilisers should be applied to *Miscanthus* in comparison to switchgrass. This is in line with the available price information for Greece on this subject.

Energy

The total energy ratio (energy output - energy input) of the establishment and production processes for both switchgrass and *Miscanthus* grown in the United Kingdom was calculated by Bullard and Metcalfe (2001). The main differences between switchgrass and *Miscanthus* is that *Miscanthus* requires extra energy inputs for the production of the rhizome starting material, whilst switchgrass can be seeded. In the production process of the rhizomes extra energy inputs are required for lifting, harvesting, grading and storing the rhizomes. This process requires extra machine equipment. Planting the rhizomes also requires specific machinery, whilst a standard cereal drill can be used for drilling the switchgrass seeds. The other energy input Whilst the required energy inputs are higher for *Miscanthus* from year 4 onwards. The energy outputs are also much higher because of a higher yield in the years 4 to 20. This results in a higher overall energy ratio for *Miscanthus* compared to switchgrass.

Weed and pest control

In all countries the costs per tonne DM of weed and pest control for switchgrass are very low, except for the United Kingdom. Relatively a higher amount is spent on herbicides in estimated UK cost calculation. The fact that most countries spray only once in the first year is explained by the importance of effective weed control during establishment, which is well known for both *Miscanthus* and switchgrass. Specific herbicide applications or mechanical weed management methods will vary tremendously depending on site, weed burden and species composition (Bullard and Metcalfe, 2001). The need to control weeds in the first year may be a bit higher for switchgrass in comparison to *Miscanthus* since seedlings are smaller and may grow slower than tillers emerging from *Miscanthus* rhizomes. Mowing above seedling height may be used as a means of weed control in switchgrass. In later years the larger number of tillers in switchgrass compared to *Miscanthus* may make weed control measures less necessary in switchgrass than in *Miscanthus*.

The application of herbicides and agrochemicals in Booth, Walker and Cook (2001) is only specified as costs per input per year. The amounts needed are unknown.

Irrigation

Irrigation only takes place in Southern European countries. In Italy the costs for irrigating switchgrass are 10,67 Euro per tonne DM, this is much higher than the costs in Greece: 6,32 Euro per tonne DM. For Greece there is also information on the costs of irrigating *Miscanthus*, these are 12,63 Euro per tonne DM and even higher than the costs of irrigating switchgrass in Italy. This corresponds to observations in Italy and Greece that switchgrass requires less irrigation than *Miscanthus*. Despite a relatively high water use efficiency, *Miscanthus* has a high water demand (Walsh et al, 1997).

Conclusion

In general switchgrass seems to perform a bit better than *Miscanthus* concerning the environment, because of the better performance of switchgrass on irrigation, low input for establishment and possibly lower fertilisation. Not on every subject it is clear which perennial grass performs better because basic underlying assumptions were not always known and comparable. If only the energy inputs are concerned switchgrass performs better than *Miscanthus* on energy, but when the overall energy ratio is concerned *Miscanthus* performs better, because of the higher yields.

Literature

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Hallam, A., I.C. Anderson and D.R. Buxton, 2001. Comparative economic analysis of perennial, annual, and intercrops for biomass production.

Walsch, M., S. McCarthy, (Ed), andothers, 19997. *Miscanthus* Handbook. Hyperion FAIR 3-CT96-1707.

9.3 Economic aspects of switchgrass utilisation for energy conversion

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Approach

Economic cost items that are relevant when using switchgrass as a fuel include:
- Switchgrass growing and harvesting,
- Switchgrass preparation into suitable fuels,
- Storage and transportation,
- Adaptations to energy conversion equipment,
- Maintenance cost of energy conversion equipment,
- Conversion efficiencies of energy conversion equipment.

In general, costs are dependent on the specific processing chain chosen for generating electricity, heat, combined heat and power (CHP), or liquid fuels. However, for each end product, several processing routes can be conceived. As an example, two possible conversion chains for the generation of electricity from switchgrass are given in Table 1.

Table 1. Description of two possible conversion chains for switchgrass.

Chain 1	Chain 2
Switchgrass growing and harvesting	Switchgrass growing and harvesting
Baling and field storage	Baling and field storage
Bale transport to power plant	Liquefaction into bio-oil
De-baling and grinding	Bio-oil transport to power plant
Fuelling into a dedicated power plant for biomass-derived fuels	Fuelling into a co-firing boiler suitable for coal and biomass-derived fuels
Electricity generation	Electricity generation

So, not only are there several energy applications, the potential routes to produce the various end-products are also numerous. Van den Heuvel (1996) gave a broad, but still limited, review of potential processing routes. Of course, one could argue that an assessment should be based on currently available technologies; and this certainly limits the number of alternatives worth consideration. However, switchgrass, is not a biomass fuel of today, but a potential biomass fuel of the future, and, therefore, it seems to be more interesting to include future energy conversion technologies into the evaluation. A similar consideration applies for all other candidate European-grown energy crops, such as *Miscanthus*, reed canary-grass, and short rotation coppice. In the beginning of this investigation into the potential of switchgrass as an energy crop, it was decided to focus on a comparison with *Miscanthus*. Switchgrass and *Miscanthus* show large similarities in terms of the physical and chemical properties of the harvested products. This particularly applies to their moisture contents and to their ash contents. On the other hand, their contents of potentially corrosive elements such as potassium and chlorine are quite different. In view of these facts, and under the circumstance of uncertain conversion routes, an economic comparison at the level of the harvested products, rather than at the level of final products seems to be the most appropriate.

In the following analysis, the harvested products are assumed to be stored in stacked bales covered with tarpaulin, located in the field from where they were harvested. LEI-DLO prepared the production cost analysis of this product (see elsewhere in this report). This chapter reviews those data in view of energy applications.

Methodology

Cost calculation

The primary purpose of the analysis is to derive the production costs of switchgrass fuel in terms of Euro per energy unit (Euro/GJ). The energy unit selected is the net calorific value at constant pressure (NCV_p) as defined in ISO 1928 (1976). Although defined for solid mineral fuels, the definition equally applies to solid biomass fuels. In some technical and economic analyses of energy conversion processes the gross calorific value (GCV), defined by the same ISO standard, is more suitable. However, an arithmetical conversion between the two types of calorific value is possible if the fuel moisture and hydrogen contents are known. That is, according to the following expression:[9]

$$GCV_p\,[MJ/t] = NCV_p\,[MJ/t] + 21825.86 \ x \ H + 2442.2 \ x \ m,$$

where H is the hydrogen content - not bound as H_2O - of the fuel, and ? is the fuel’s moisture content. The formula applies for any type of analysis basis (wet; dry; or dry and ash free), provided that the same basis is consistently applied. According to the referred ISO standard, the gross calorific value is determined at constant volume (GCV_v) for an analysis sample. Based on that measurement, the NPV_p is then calculated for the state of the analysis sample, defined by its hydrogen content (H_{Rw}), oxygen content (O_{Rw}) and moisture content (μ_{Rw}), from:[10]

$$NCV_{pRw}\,[MJ/t] = GCV_{vRw}\,[MJ/t] - 21211 \ x \ H_{Rw} - 77.48 \ x \ O_{Rw} - 2442.2 \ x \ m_{Rw}$$

In reality, the moisture contents of both switchgrass and *Miscanthus*, when baled and piled, are expected to be about 10-20%. Arithmetical conversion of the calorific values to the any actual moisture content proceeds by using the following equation:

$$NCV_{pAw}\,[MJ/t] = NCV_{pRw}\,[MJ/t] \ x \ \frac{1 \ m_{Aw}}{1 \ m_{Rw}} + 2442.4 \ \frac{m_{Aw} \ m_{Rw}}{1 \ m_{Rw}}.$$

where the subscripts R and A denote the fuel condition in the reference state (R) and in the actual condition (A), respectively. The equation applies to fuel properties expressed on a wet basis. This is indicated by means of the subscript w.

Productivity data for energy crops such as switchgrass are usually given on a dry-matter basis, i.e. t_0/(ha.yr). The dry matter is also the usual basis for the determination of production cost, i.e. they are normally expressed in terms of Euro/t_0. Since switchgrass is not utilised in the dry form, a recalculation must be made to adjust for the actual moisture content. This proceeds by means of the following equation:

$$C_{MA}\,[Euro/t_A] = C_{MR}\,[Euro/t_R] \ x \ \frac{1 - m_{w,A}}{1 - m_{w,R}},$$

where C_{MA} is the production cost per tonne at the actual moisture content as utilised, and C_{MR} is the production cost per tonne at the reference moisture content. If the reference moisture content is 0%, and the actual moisture content is 20% on a wet basis, then the equation becomes:

[9]Based on ISO 1928 (1976). For the expression to apply, the unit of the calorific values is in MJ/t, and the contents of hydrogen and oxygen, as well as the moisture content are expressed as fractions.
[10]Based on ISO 1928 (1976). The subscript R denotes the state of the analysis sample, which is taken as the reference state.

$$C_{MA}\,[Euro/t_{20}] = C_{MR}\,[Euro/t_0]\ x(1\ -0.20).$$

Thus, to determine energy equivalent costs for practical moisture contents, given dry-matter production costs, proceeds as follows:

$$C_{EA}\,[Euro/GJ] = \frac{C_{M0}\,[Euro/t_0]\ x(1 - m_{Aw})}{NCV_{pRw}[MJ/t]\ x\dfrac{1-m_{Aw}}{1-m_{Rw}} + 2442.4\,\dfrac{m_{Aw}-m_{Rw}}{1-m_{Rw}}}\,x\,1000.$$

By making use of the subscripts E and M, the energy basis and the mass basis of the unit costs (C) are distinguished. The applicable parameter values are reported in the next Section.

Other economic issues

In the introduction, it was explained why the economic value of a fuel does not only depend on its unit energy value. Other determining factors include utilisation issues like required adaptations to energy conversion equipment, and associated maintenance cost of energy conversion equipment. Especially fuel properties with regard to corrosion are very relevant. Fuels of a particular corrosive nature make additional investments into less vulnerable equipment necessary, and also result in increased maintenance costs. These increased costs of fuel utilisation can be translated into reduced fuel values. Quantification depends, however, on the applicable conversion technology.

For this generic study a single assumption with regard to the utilisation technology would be inappropriate. This issue is therefore merely illustrated with an example, to show the relevance of the matter. The example compares the utilisation of wood and straw in non-CHP district heating plants. Straw is a well-known corrosive fuel, due to its high contents

of alkaline matter. The example was selected in view of the availability of data. Since no such data are available for switchgrass, the example should be interpreted with care.

Elaboration

Basic technical data for the determination of unit energy costs are given in Table 2.

Table 2.

Reference states (analysis sample)		
μ_{Rw}	23.70%	Measured
H_{Rw}	4.37%	Measured
O_{Rw}	32.69%	Measured
GCV_{vRw}	14294 MJ/t	Measured
NCV_{pRw}	12763 MJ/t	Calculated
Actual state (utilisation state)		
μ_{Aw}	20%	Assumed
NCV_{p20w}	13263 MJ/t	Calculated

Elsewhere, in the reporting of this project, the production costs (C_{M0} [Euro/t_0]) for switchgrass are analysed and compared with the production costs for *Miscanthus*. They are reviewed in Table 3. This table also shows the resulting energy values (C_{E0} [Euro/GJ]).

Table 3.

Case	Greece	Italy	United Kingdom	Germany	Netherlands
C_{M0}(Euro/t_0)/a	18	23	23	31	45
C_{E20} (Euro/GJ)	1.09	1.39	1.39	1.87	2.71

a/: Source LEI-DLO

To illustrate the effect of corrosiveness on fuel value, a 2 MW non-CHP district heating plant was considered for two fuel types: wood and straw. In terms of corrosiveness, switchgrass is similar to wood. *Miscanthus*, on the other hand, shows rather detrimental specifications. Straw is one of the least attractive fuels in terms of corrosiveness.

Table 4.

Content (mass %, dry basis)	Wood	*Miscanthus*	Straw	Switchgrass
Cl	0.01%	0.22%	0.42%	0.07%
K	0.15%	0.49%	1.30%	0.01%
Ca	0.77%	0.23%	0.31%	0.03%

Economic performance data on wood and straw-fuelled systems were reported in two Danish studies,[11] and these are taken for our elaboration. General parameter values are shown in Table 5.

Table 5.

Boiler capacity /a	2	MW
Conversion efficiency /a	100%	
Annual energy /a	11200	MWh before distribution loss/yr
=	11200	MWh before conversion loss/yr
=	0.040	PJ_0/yr
Project duration /a	20	yr
Discount rate /b	10%	

a/ Wood for energy production (technology, environment, economy), Centre for Biomass Technology, Denmark, 1999.
b/ This study.

Specific parameter values are given in Table 6. The table also shows how the difference in fuel quality can be expressed in terms of Euro/GJ. The resulting difference in value is about 1 Euro/GJ. This appears to be a quite relevant issue, if straw is concerned. It is uncertain to which extent this consideration will apply to switchgrass.

[11] Serup, Falster, Gamborg *et al.* (1998) and Serup, Falster, Gamborg *et al.* (1999).

Table 6.

Cost item	Wood /a	Straw /b	
Capital (Euro), (differing ones only)			
Heating plant	896,000	1,186,000	
Annualised capital costs	105,244	139,307	Euro/yr
=	2.61	3.46	Euro/GJ
Operating costs (Euro/yr), (differing ones only)			
Maintenance, heating plant	17,000	26,000	
Electrical power consumption	11,000	9,000	
Other costs	9,000	10,000	
Total operating costs (differing ones only)	37,000	45,000	Euro/yr
=	0.92	1.12	Euro/GJ
Grand total differing costs	3.53	4.57	Euro/GJ

a/ Wood for energy production (technology, environment, economy), Centre for Biomass Technology, Denmark, 1999.
b/ Straw for energy production (technology, environment, economy), Centre for Biomass Technology, Denmark, 1998.

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10 Management guide for planting and production of switchgrass as a biomass crop in Europe[12]

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Introduction

Switchgrass (*Panicum virgatum* L.) is a warm season perennial herbaceous grass that is established from seed. It develops rhizomes and is also deep rooting, often more than 2 m. It grows 50-250cm tall depending on the variety and climatic conditions. It has the C4 photosynthetic pathway and is an efficient user of nitrogen and water. This makes it potentially a very productive grass. Productivity will vary between 6 tonnes dry matter (DM)at low fertile Northern European sites up to 25 tonnes at fertile Southern European sites. If properly managed it has long-term productivity potential (>15 years) with a high level of sustainability.

Switchgrass is indigenous to North America and is found from Mexico into Canada but it does not occur naturally above the 55 0 N latitude. There are two main types: lowland types that are found on wetter sites such as flood plains. They have tall, thick, coarse stems and bunch growth habit. The upland type is adapted to drier habitats. It has thinner stems than the lowland type and stem number is greater. Some have a turf -like growth habit.

Switchgrass is best compared to *Miscanthus*, another C4 biomass grass. Compared to *Miscanthus* (gigantheus), switchgrass is smaller, thinner and generally leafier. As it is established from seed, establishment is less expensive and involves less risk than *Miscanthus*, which is propagated by rhizomes, which is more expensive. There are indications that switchgrass is more drought tolerant and may do better under low fertility (low input) conditions

Applications

In the USA switchgrass is used for erosion control and to provide forage under hot and dry conditions. In recent years switchgrass has been intensively studied in North America and more recently in Europe as a potential biomass crop for power production through direct combustion and possibly for lignocellulosic ethanol production. Other uses of switchgrass include fibre production, and wildlife habitat improvement.

Growth cycle

Shoots emerge in spring when soil temperature rise above 10 C. Growth can be very rapid with up to 75% of biomass being formed by mid-summer when flowering occurs. After flowering is complete, stems become lignified and start to senesce, as the plant becomes dormant. In southern European countries the growth cycle may be complete by late summer. During senescence minerals are relocated from leaves and stems to roots and rhizomes where it is stored for the next growth cycle. This natural process improves the quality of the biomass for combustion.

Site selection

Deep soil that has good water holding capacity and adequate drainage is best but switchgrass is adapted to a wide range of soils. Shallow soils, stony soils and occasionally waterlogged soils are also suitable. When grown under low soil fertility and pH (acidity) it will have relatively high yields compared to temperate grass species or energy tree crops like willow coppice

[12] These guidelines are based on available literature and three-year Europe wide small plot experiments. Therefore the guidelines should be seen as preliminary. Improved guidelines should become available as large-scale experiments are conducted in Europe. See www.switchgrass.nl

Previous crop

Spring and summer germinating weeds, especially perennial weeds and volunteers can be a serious threat to switchgrass establishment. Sites with severe weed problems should be avoided but if this is not possible weeds should be treated well in advance of planting. To reduce the risk from weeds it is important to plan ahead. Start your weed elimination strategy in the year before planting. Control of perennial weeds will be better because any re-growth can be dealt with before the switchgrass is sown. Take into account any specific requirements resulting from the previous crop for example, avoid leaving surface residues because it can interfere with sowing and prevent good seed to soil contact.

Site conditions

Switchgrass is slow to establish and it is important to follow basic guidelines that have proved successful in North America and Europe. Eliminate perennial weeds in particular since these are the most difficult to control after the crop has been planted (see previous crop). Prior to cultivation, compacted areas should be sub-soiled. After ploughing, use any secondary cultivation necessary to produce a firm fine seedbed. It has been shown both in the USA and recently in Europe that no-till drilling is also possible.

Soil fertility

Switchgrass is well adapted to low fertility and acid soil conditions. It has a large and deep root system that is very efficient in scavenging nutrients. It utilises mycorrhizae in taking up phosphorus.

Under ideal conditions one should aim for a neutral pH status at planting. In the first year no nitrogen should be applied because it is not necessary for the development of the crop and can promote weed growth leading to competition with seedlings and possibly smothering them. Phosphorus and potassium should be applied if soil availability is low. In later years application of nutrients should be at a level that anticipates rising productivity and also takes into account losses of minerals in harvested biomass. Normally stems are harvested when they are dead, the mineral content is low, and fertiliser application to compensate for this loss may only be required every few years. Nitrogen requirement is low and some studies show that soil reserves, N re-mobilised from roots and atmospheric deposition may be adequate in NW European conditions. On soils of low fertility or where irrigation is applied additional N may be required. The first European studies show that between 0 to 50 kg N/ha/year is adequate for NW European sites while at higher productive sites in southern Europe 50 to 100 kg N/ha/year should be adequate. More specific recommendations for quantity of nutrients cannot be made because it will depend on the fertility status of the site, however phosphorus and potassium levels can be kept low. High N applications may contribute to lodging. Lodging has been observed at several experimental sites in NW Europe and can reduce yield and increase moisture content of the biomass.

Variety choice

A number of varieties are available from North America that have been found to be adapted to European conditions. Variety choice will be governed by the latitude of the site on which planting is intended. Varieties originating from Southern American areas will do best in Southern locations in Europe however they still are productive in Northern Europe but over-winter survival may not be as good as varieties of northern origin. Results from the European switchgrass network show that varieties can be grown further north in Europe than on the American continent probably because maritime influences moderate the climatic conditions.

A wide range of varieties has been tested under European conditions and many have proven to be well adapted. The following varieties have both given good results at their area of adaptation in Europe and are commercially available (in the USA):

Variety Cave-in-Rock is adapted to NW European areas (UK, NL, D).

Variety Kanlow is adapted to more southern areas (Southern UK and D, Northern IT). The variety can experience winter survival problems at more northern latitudes especially in the first year.

Variety Alamo is best suited to Southern regions of Europe (GR, IT). It may not survive winter in Northern Europe, especially in the first year, and quality will be low.

Planting

Seed can be sown in a conventional manner with a drill or direct-drilled (no-till) or broadcast. Whatever method is used, rolling before and after sowing is often desirable, particularly when seed is broadcast to ensure good seed to soil contact but don't roll if the soil is wet because surface compaction or crusting might result. Sowing depth should be about 10mm; seed sown deeper than this may fail to establish. Seed sown into a loose seedbed may lodge later.

Timing of planting

Sow switchgrass when the surface soil is warm. Best results will come from soil temperatures above 10C and when there is some moisture in the seedbed but not when it is too wet. Avoid dry seedbeds, because it can result in poor germination and establishment. In northern Europe sowing would normally take place in late April or May. A good guide to the conditions required for planting switchgrass is that they about the same as that for planting *maize (Zea mays*). When switchgrass is sown too early the seedlings will not be able to compete with the weeds due to the relatively high temperature requirement for the grass.

Seed rate

Seed rate is based on the number of live seeds and germination rate (pure live seeds). Germination rate can vary widely with switchgrass depending on the age of the seed. Freshly harvested seed has a high dormancy and often seed is stored for a year before it is used. Germination can be improved by stratifying seeds. Before seed is purchased it will have been germination tested and the percentage of pure live seed calculated, from the information the seed rate is calculated. Still, storage may change seed dormancy and it is recommended that a simple germination test be performed to check seed germination rate. Very little information is available on optimum seeding rates in Europe. The best estimate is that a seeding rate of 400 PLS per m^2 should be adequate in NW Europe and 200 PLS per m^2 southern Europe. This means that the seed rate will be between 10 kg and 20 kg /ha.

Drilling equipment

Switchgrass seeds are small, and have a hard polished skin. There are about 500-1000 seeds/g depending on the variety. If a cereal drill is used, it may require a small seeds roll to be fitted. The seed drill must be capable of sowing the seed evenly along the row. Row width should be around 15cm.

Weed control

Growth is slow in the first year and seedlings compete badly with weeds. Keep in mind that weeds only have to be managed so that enough switchgrass seedlings survive the first winter and re-grow in spring. When this can be achieved generally no further weed control is necessary in following years as switchgrass will out-compete weeds when temperatures increase in spring.

Good and timely seedbed preparation, possibly preceded by a false seedbed, is necessary.

To increase the chances of adequate establishment and re-growth after the first winter, herbicides can be used. Keeping in mind that at the moment, to our knowledge, no herbicides have been specifically been registered for switchgrass. Glyphosate can be applied before seedbed preparation. Atrazine can be safely used pre or post emergence. To check broadleaf weeds ioxynil, bromoxynil, mecoprop, bentazone, and CMPP have been used on switchgrass.

Some of the herbicides can cause scorching and check growth. Use all herbicides at low dose rates and apply more if necessary. The most important mechanical weed control measure is mowing of weeds just above switchgrass height, when necessary. It is important not to cut the leaves switchgrass seedlings because this can seriously jeopardise the ability of the plant to survive the winter.

Pest and disease control

Diseases have not been a problem in switchgrass in Europe but crops still require regular inspection. No serious problems from pests have been reported. If there is a problem from rabbits, field margins should be fenced.

Yield development

Depending on the soil type optimal productivity is reached in 2-3 (on light soils) to 4-5 years (on heavy soils. Yield in the first year is low and it at northern latitudes may not be economic to harvest. In the second year yields can be 8-10 t dm/ha and increase further in the third year. Early frosts or droughty conditions may delay the development of full yield potential.

Management of the established crop

Established switchgrass can compete effectively with weeds when temperatures rise in spring. Lodging can be a problem.

Harvest

When switchgrass is grown for biomass (energy, fibre, etc) delayed harvest in winter/early spring is recommended. Harvesting the crop before senescence (in fall) will lead to lower winter survival and reduced spring re-growth and possibly leading to stand loss. The harvest is executed using normal grass baling methods and equipment. If the crop is to be stored for a longer period the moisture content should not be above 15-20%. The rate of dry-down and the moment of re-growth determine the harvest window in winter/early spring. If the crop is not lodged, the crop has had time to senesce and the stems are thin enough, adequate moisture content reduction will be reached before re-growth in spring.

Production cost

Preliminary estimates of the production cost (without land cost) of switchgrass vary between 24 Euro per tonne DW in Greece and 62 Euro per tonne DW for the Netherlands. The costs should compare favourably to *Miscanthus* since the cost and associated risk of establishment is lower.

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Annex: A switchgrass bibliography

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Introduction

Switchgrass occurs naturally east of the Rocky Mountains and south of 55°N latitude down into Mexico and Central America (Moser and Vogel, 1995). It is one of the main species of the North American tall grass prairies. In North America the grass is planted for forage, erosion control and wildlife cover (Moser and Vogel, 1995; Nielsen, 1944). The species can also be found on other continents where it is grown for forage production (Osman, 1979; Stritzler al., 1996). Since the late 80's the species has been studied as a biomass crop for renewable energy production in the USA and Canada. The main uses are for electricity production through gasification, co-combustion in coal plants and ethanol production for transportation fuel (Samson and Omielan, 1992; Sanderson et al., 1996; Turnhollow, 1991). Recently other uses have been added to the switchgrass potential like paper pulp (Girouard and Samson, 1998; Radiotis et al., 1996) and fibre reinforced composite materials.

Switchgrass was chosen by the US-DOE as a model lignocellulosic biomass crop for energy production because of its high productivity across a wide geographic range, suitability for marginal quality land, low water and nutrient requirements and environmental benefits (McLaughlin et al., 1996; Sanderson et al., 1996). The environmental benefits include low pesticide requirements, erosion control, good wildlife cover and potential for soil improvement (McLaughlin et al., 1997; Sanderson et al., 1996). Compared to annual row crops herbaceous energy crops like switchgrass reduce erosion by 95% and pesticide use by 90% (Hohenstein and Wright, 1994).

Plant description

Switchgrass is an erect perennial warm-season (C_4) grass that resembles a bunchgrass, it spreads slowly by seeds and rhizomes. The plant has erect stems that can be between 0.5 and 2.7 m tall and often have a reddish tint. The inflorescence is an open panicle 15 to 50 cm long the root system can be up to 3 m deep (Beaty et al., 1978; Christian and Elbersen, 1998; Moser and Vogel, 1995). A distinct characteristic is the white hairs where the leaf attaches to the stem.

The seed

Switchgrass has relatively small seed that can have high levels of dormancy especially just after harvest. Seed weight depends on variety and environmental conditions and varies between 70 and 200 mg 100^{-1} (Christian and Elbersen, 1998; Moser and Vogel, 1995). The seed is smooth and flows easily thought machinery, making seed drilling easy. High dormancy levels can be reduced by storing at room temperature for up to 4 years, though may also reduce seedling vigour (Moser and Vogel, 1995). Dormancy can also be broken by vernalisation when the seed is planted early in the field when conditions are cold and wet (Moser and Vogel, 1995; Smart and Moser, 1997). Several seed treatments have been tested to increase germination levels of switchgrass including "wet chill" seed vernalisation, sulphuric acid treatments and seed priming (Beckman et al., 1993; Tischler et al., 1994; Parrish et al., 1997). New varieties are being developed with reduced seed dormancy (Ocumpaugh et al., 1997). Seed production typically varies between 220 and 560 Kg ha^{-1} but can reach 1000 kg ha^{-1} (Moser and Vogel, 1995). Prices for seed vary considerably from year to year due to bad harvests and fluctuating demand.

Seedling morphology

Two types of seedling morphology are generally distinguished in grasses; the "panicoid" type and the "festucoid" type (Fig 2) (Hyder et al., 1971; Tischler and Voigt, 1987). Most cool season (C_3) grasses, like tall fescue (*Festuca arundinacea* L.) and ryegrass (*Lolium perenne* L.), have festucoid seedling morphology. Warm season (C_4) grasses, like switchgrass, have panicoid seedling morphology. In festucoid seedlings the coleoptile elongates while the crown node, from which secondary roots and leaves originate, remains at seed level. In panicoid seedlings the mesocotyl (also called the subcoleoptile internode) elongates and pushes the small coleoptile to the soil surface, thus placing the crown node just under and sometimes at the soil surface (this feature makes seedlings easy to recognize in the field). Adventitious (secondary) roots develop from the crown node if moist conditions exist for several days (Newman and Moser, 1988). When the soil surface is dry no adventitious (secondary) roots will develop at the crown node, so the seedling will depend on the primary root and supply capacity through the mesocotyl for water and nutrients. Since the capacity for water and nutrient supply through the mesocotyl is small this will eventually limited seedling growth (Redman and Qi, 1992). Another detrimental effect is that the seedling is only loosely attached to the soil by the thin mesocotyl and can easily break off. Thus, establishment of panicoid seedlings can be divided into two critical phases for which sufficient moisture is required. Adventitious (secondary) roots develop from the crown node if moist conditions exist for several days (Newman and Moser, 1988). For example, the seedling of blue grama (*Bouteloua gracilis*) requires one period of moist soil conditions to germinate and emerge and a second moist period of about 3 days 2 to 8 weeks after emergence to form secondary roots at the crown node (Wilson and Briske, 1979). A seedling can be considered established when sufficiently long secondary roots have been formed so that the seedling can grow to sufficient size before the onset of winter (Hyder et al., 1971; Newman and Moser, 1988; Ries and Svejcar, 1991). Winter survival is generally considered the real test of plant establishment. Germplasm has been selected for lower crown node placement which is expected to have superior establishment characteristics (Elbersen et al., 1998; Tischler and Voigt, 1995; Tischler et al., 1996).

Ecotypes, ploidy levels and varieties

Switchgrass is highly polymorphic and largely self incompatible (Talbert et al., 1983; Taliaferro and Hopkins, 1997). The basic chromosome number of switchgrass is x = 9. The ploidy levels of switchgrass vary from diploid (2n=18) to duodecaploid (2n=108) (Hulquist et al., 1996; McMillan, 1959; Nielsen, 1944; Riley and Vogel, 1982). Some populations (varieties) like KY 1625 consist of plants with different ploidy levels. Recently Hopkins et al. (1996) determined that many varieties that were considered to be hexaploids are in fact octoploids. In Table 1. the ploidy levels of most existing switchgrass varieties is given as could be determined from the literature. Seed weight varies with environmental conditions and harvest date but is generally larger for octoploid than for tertaploid varieties.

Two ecotypes are generally defined based on morphological characteristics and habitat preferences. Lowland types are generally found in floodplains, they are taller, more coarse, have a more bunch type growth habit, and may be more rapid growing than upland types (Moser and Vogel, 1995; Porter, 1966). Upland types are found in drier upland sites, they are finer stemmed, broad based, and often semi-decumbent. Lowland ecotypes have more of a bunchgrass form with an elevated crown (Porter, 1966), which can increase cold injury problems. Wullschleger et al. (1996) found that maximum single leaf photosynthesis rates were higher for lowland than for upland varieties. After a drought period, later in the season, this difference was reversed, with lowland varieties having lower maximum single leaf photosynthesis rates than upland varieties. Lowland types are primarily tetraploid while upland types are hexaploid to octoploid but the exact relationship between ploidy level and ecotype remains unclear (Gunter et al., 1996; Hopkins et al., 1996). Porter (1966) suggested that upland and lowland types are genetically different. Artificial hybridization between lowlands and uplands have largely been unsuccessful (Taliaferro and Hopkins, 1997). For some varieties there does not seem to be agreement in the literature on the exact ecotype. In Table 1. the ecotype of several varieties is given. Hulquist et al. (1996) suggest that lowland types may be better suited as biomass fuel plants. In the southern USA lowland varieties like Alamo and Kanlow generally yield more dry matter than upland varieties (Parrish et al., 1997). Unfortunately it seems that northern ecotypes are mostly of the upland type. New lowland and upland varieties are being developed specifically for biomass production for southern and northern regions (Taliaferro and Hopkins, 1997).

Beaty et al. (1978) made a distinction between bunch and sod forming switchgrass types; it appears that most switchgrass varieties are of the bunchgrass type.

According to Moser and Vogel (1995) the main factors determining area of adaptation of a variety are response to photoperiod, precipitation and humidity. Decreasing daylength will induce flowering in early

summer. When different varieties are grown in the same site northern ecotypes will remain shorter, flower earlier and mature earlier than southern ecotypes. Also, production of biomass will be considerably less compared to southern types. Samson et al. (1997) compared DM yield and days to maturity. The highest yielding variety, Cave-in-Rock (>12 tons DM) matured in 135 days while the lowest yielding variety, Dacotah (<6 tons DM) matured in less than 100 days. Cave-in-Rock originates at 38? 30´ and Dacotah at 46? 30´ northern latitude. Van Esbroeck et al. (1997) found that cultivars differing in length of vegetative growth produced approximately the same number of leaves before panicle emergence. The main characteristic associated with a long period of biomass accumulation was a slow rate of leaf appearance.
Southern ecotypes moved north, will often fail to mature (and produce seed) before the end of the growing season. The failure to mature can prevent winter hardening which can lead to poor winter survival (Moser and Vogel, 1995). With generally mild winters this should be less of a problem in Western Europe. Still, in the establishment year, this may cause problems if young plants fail to winter harden properly. The quality of late maturing varieties can also be reduced because biomass will not be dry at harvest (D. Christian, pers. comm.) and nutrient content of harvested biomass may be high because nutrients have not been translocated to below ground parts (Sanderson and Wolf, 1995). This will reduce the potential for regrowth in the spring and will increase the ash content of the above ground parts, which is an undesirable feature for energy conversion, paper pulping and other fibre uses. It has been observed that southern cultivars moved too far north will initially produce good harvests which can not be sustained over time as the stand thins out.

Management

It often takes several years of careful management to establish a good stand of switchgrass which will last for more than 20 years under good conditions (Myers and Dickerson, 1984). The yield of a stand can take a few years to reach maximum potential (Christian and Elbersen, 1998). The delay in maximum production is most frequently experienced on cool wet clay soils in northern regions and in northern regions where sufficient soil moisture for seedling development is a problem (Samson pers. comm.).
Seedling establishment is the most critical stage in the development of the crop. Most varieties are established by seed. A notable exception are the cultivars Miami, Stuart and Wabasso which originate in Florida, they are generally propagated vegetatively.
The most important factors in establishment of switchgrass are seed placement, seed dormancy, water availability, temperature, weed competition and time of planting. The use of herbicides is often required to ensure good establishment. Herbicide recommendations may differ between northern and southern climates and between lowland and upland varieties.
It is recommended to do a seed test and if necessary to use seed dormancy breaking methods. The official seed testing method includes a period of cold stratification. Since this is generally not what the seed will be exposed to if planted in the field a simple seed test is recommended to realistically estimate field germination before seeding (Moser and Vogel, 1995; Wolf and Fiske, 1995). Wolf and Fiske (1995) recommend a "wet chill" vernalisation to break dormancy if seed germination is lower than 40%. Seeding (drilling) is generally done on a pure live seed (PLS) basis (Moser and Vogel, 1995). PLS is calculated by multiplying the purity (the ratio of actual seed to total weight) by the germination:
If the purity is 90 % and germination is 70 %;
PLS = 0.90 (purity) x 0.70 (germination) = 0.63 or 63%.
So for 1 kg PLS 1.59 kg bulk seed is required.

Though most seeding rate recommendations are based on weight (kg ha^{-1}) the number of germinants per m^2 is probably a better measure. Recommended seeding rates range between 2.4 and 10 kg PLS ha^{-1} (Bransby et al., 1997; Moser and Vogel, 1995; Ocumpaugh et al., 1997; Wolf and Fiscke, 1995) which translates to 200 to 800 PLS m^{-2}. Small seeded varieties would require a lower seeding rate (kg ha^{-1}) than heavier seeded varieties. The desired number of seedlings (plants) per m^2 in the first year that is required to form a good stand will vary with environmental conditions. Though 10 to 20 seedlings (plants) per m^2 can be enough to establish a adequate stand most reported seedling rates are much higher; between 80 and 300 seedlings per m^2 (Christian and Elbersen, 1998; Peters et al., 1989; Vassey et al., 1985; Vogel, 1987).

Time of seeding

Time of seeding is an important factor in establishment success of switchgrass. Both early (Moser and Vogel, 1995; Smart and Moser, 1997; Vassey et al., 1985) and late (Parrish et al., 1997; Wolf and Fiske, 1995) seeding have been advocated. Early seeding has the benefit that cold and wet conditions break seed dormancy (Moser and Vogel, 1995). The chance of sufficient rain events is increased which will ensure that soil moisture is available for seed germination and emergence, and for secondary root development (Smart and Moser, 1997). Also, the seedlings will have sufficient time to develop before the autumn, increasing winter survival. The main problem of early seeding is that soil temperatures are low which causes slow germination and seedling development. According to Madakadze (1997) the base temperature for germination is variety dependent and ranges from 5.5 to 10.9? C. Hsu et al (1985) calculated a minimum germination temperature of 10.3? C for Blackwell and Cave-in-Rock switchgrass. Kiniry et al. (1996) assumed a base temperature for Alamo switchgrass growth of 12 °C. Thus, switchgrass growth will be relatively slow in spring compared to most problem weeds; increasing relative competitiveness of these weeds. Late seeding will be preferred to reduce weed competition but it may increase drought problems, reduce emergence percentage and can increase the chance of winter-kill if the growing season is short.
In southern Texas switchgrass is sometimes planted in late summer or fall. The seedling will develop sufficiently to survive the mild winter; still, winterkilling is not uncommon (Ocumpaugh et al., 1997). In some areas of the northern Great Plains “dormant plantings” are made in late fall so the seed overwinters, is vernalized and germinates in spring as the weather warms up but spring plantings are generally preferred (Moser and Vogel, 1995).

Seedbed preparation and planting

Seedbed preparation should be such that weeds are avoided and accurate seed placement is possible. Measures include planting a smother crop such as a small grain (Wolf and Fiske, 1995; Ocumpaugh et al., 1997). Having corn as a previous crop can increase weed problems since many problem weeds in corn are also a problem in switchgrass. Planting can be done no till or in a smooth clean and firm seedbed. A precision seed drill should be used with a planting depth of about 1cm (Christian and Elbersen, 1998; Moser and Vogel, 1995). A firm seedbed will also facilitate proper seed placement. It is recommended that before and after drilling the soil is well compacted to assure good seed soil contact.

Weed control

Switchgrass is often established without herbicides in the USA. However, weed competition is a mayor reason for stand failure. Most seedings will require some form of weed control measure. Frequently weed pressure is so heavy that it is hard to find switchgrass seedlings in the field. Because of this many switchgrass plantings are given up unnecessarily, when measures can still be taken to ensure stand establishment. It is important to be able to recognise switchgrass seedlings in the field. Application of herbicides and mowing will generally be sufficient to allow switchgrass to eventually out compete weeds as temperatures increase and a good stand will develop. A list with herbicides that have been used in switchgrass and appropriate references is given in Table 2.

A desiccant or a contact herbicide is generally used several weeks ahead and again just before seeding (Wolf and Fiske, 1995). Glyphosate, paraquat and herbicides with hormonal action like 2,4-D, dicamba or MCPA are often used. The second application just before seeding should be at a lower rate.
Switchgrass has seedling and mature plant tolerance to atrazine (and also simazine) (Martin et al., 1982) herbicides which are frequently used at seeding (Christian and Elbersen, 1998; Moser and Vogel, 1995). Still, there are indications that atrazine and also simazine can cause injury to small seedlings, especially to lowland ecotypes (Samson, pers. comm.; Bovey and Hussey, 1991). Another problem is that the use of atrazine and simazine are not permitted or will be phased out soon in most European countries. Pre-plant incorporation of bensulide and butylate is often used in switchgrass (Bransby et al., 1997; Samson pers. comm.). In the USA imazethapyr and imazameth have been tested for use in switchgrass (Samson, pers. comm.; Vogel et al., 1997). Bensulide, butilate, imazehtpyr and imazameth are not registered in The Netherlands and probably also not in the rest of Europe. Options for pre-emergence herbicide application are limited in Europe.

For post-emergence broadleaf weed control 2,4-D is often recommended when the switchgrass seedling has at least five leaves (Moser and Vogel, 1995), or 4 fully expanded leaves (Wolf and Fiske, 1995), or 3 or more tillers (Ocumpaugh et al., 1997). Especially in the early seedling stage switchgrass can be damaged by 2,4-D and slow down establishment (Bovey and Hussey, 1991; Samson pers. comm.). Dicamba another broadleaf herbicide is also frequently used but can also damage switchgrass seedlings and slow establishment (Halifax and Scifres, 1972; Samson pers. comm.). If 2,4-D and Dicamba are applied, low rates should be used. MCPA is a mild hormone herbicide against dicots that can be applied post-emergence without much risk to grass seedlings. Bentazon, is used against dicots and is safe for C_4 grass seedlings (Samson pers. comm.). Other post emergence herbicides for broadleaf control switchgrass include sulfometuron, metsulfuron and chlorsulfuron (Bransby, 1997; Samson pers. comm.). These herbicides are not registered in The Netherlands and probably also not in the rest of Europe. In England ioxynil, bromoxynil, and mecoprop-P have been used for broadleaf weed control more than a month after seeding (Christian, pers. comm.). Bentazon, MCPA and mecoprop-P applied as late as possible are probably the safest choice for broadleaf weed control in the establishment year. Grassy weeds are harder to suppress with post-emergence herbicides. Mowing just above switchgrass height is probably the best measure against competition from grassy and also other weeds (Wolf and Fiske, 1995: Ocumpaugh et al., 1997).

In the second year applications of isoproturon, atrazine, simazine, 2,4-D, glyphosate and paraquat are used to control weeds in early spring when switchgrass has not yet emerged (Christian and Elbersen, 1998; Wolf and Friske, 1995; Ocumpaugh et al., 1997). Metolachlor, a herbicide used in corn, is also used in switchgrass (Hopkins, 1995b). In England ioxynil, bromoxynil, and mecoprop-P have been used for broadleaf weed control in the summer (Christian pers. comm.). As in the establishment year bentazon, MCPA and mecoprop-P and also 2,4-D and dicamba are probably the best choice for broadleaf weed control. Still, a well-established switchgrass stand is very competitive to all weed competition.

Row distance

Row distance is an important factor in determining switchgrass productivity. A narrow row distance will accelerate canopy closure in spring which will increase total light interception over the season and thus crop productivity. Earlier crop closure will also reduce weed competition. Problems include self-thinning, which reduces total biomass yield. Also, dense crops will have more disease and lodging problems. Several row spacing studies have been conducted in switchgrass. Ocumpaugh et al. (1997) compared row spacings of 15, 30 and 50 cm and found that in drought conditions wider spaced treatments had higher yields. Bransby et al. (1997) found that in Alabama wide spaced (80 cm) stands yielded more than narrow spaced stands (20 cm) after the first year. The yield increase was especially evident several years after establishment. Still, in the literature a row spacing of 15 to 20 cm is most common. In view of the possible weed problems and slow crop closure under low temperatures a row distance of 15 cm is probably best for the current project.

Fertilization and yield

Switchgrass will tolerate acid and infertile soil conditions that will not support cool-season grasses. Switchgrass will tolerate a soil pH of 4.9 up to 7.6 (Moser and Vogel, 1995), but will establish and grow better if pH is amended to neutrality (Jung et al., 1988). Porter reported switchgrass growing in soils with a pH of 8.9 to 9.1 (Porter et al., 1966). Taliaferro and Hopkins (1997) found that in the seedling phase cv. Kanlow and Blackwell were highly tolerant of acid soils ranging from pH 4.4 to 5.1 and concluded that breeding for increased acid soil tolerance is not warranted because of existing high tolerances.

As mentioned, fertilization (especially N) is not recommended in the first year since this will stimulate weed competition. On light soils and in southern regions a small amount of nitrogen can be given later in the season of the establishment year. After the first year fertilisation should still be delayed to later in the season when weed pressure is lower. If nitrogen fertiliser is not fully utilised by the end of the season N-carryover can increase weed competition in the following spring (Moser and Vogel, 1995). Switchgrass makes good use of organic nitrogen since highest growth rates occur when mineralization of organic N is highest (Moser and Vogel, 1995). The high rate of mineralisation and uptake by switchgrass may contribute to lodging, a problem that has been encountered in England and Canada (Christian pers. comm.; Samson pers. comm.). Biomass lodging has also been reported at high N-rates in Texas after drought (Ocumpaugh et al., 1997). On heavy soils with high N contents switchgrass will often not show a response to nitrogen for several years after establishment (Christian and Elbersen, 1998; Samson pers. comm.).

Harvest management has an important influence on fertiliser requirement of the crop. Parrish et al. (1997) harvested Cave-in-Rock switchgrass at monthly intervals from September to April. Biomass yields declined from September to November from 13.6 to 9.8 tonnes ha^{-1} and to 8.9 tonnes ha^{-1} in April. There was a 12% lower yield in the following season when the previous year's harvest had been made in September or October. It was estimated that in the period from September to senescence 10% of the biomass is translocated to the below ground parts, which included as much as 72 kg N ha^{-1}.

On light soils in Texas, with high productivity and harvests during the growing season Ocumpaugh et al. (1997) found a N-response up to 200 kg N ha^{-1}. When switchgrass is harvested for biomass after the winter most of the nutrients will be recycled within the plant or return to the soil through sheded leaves. The amount of nutrients that is removed from the system is small. The lack of a N-response on a heavy soil over several years as reported by Christian (pers. comm.) illustrates this effect.

It has been estimated that for biomass production switchgrass only requires 50 kg N ha^{-1} (Turnhollow et al., 1991). For the American great plains N fertiliser recommendations are given for grazed switchgrass depending on precipitation, they vary between 50 and 100 kg ha^{-1} N for areas with 450 and 750 mm of precipitation per year respectively (Moser and Vogel, 1995). For established stands the best guideline for N fertiliser application is probably to fertilise at the extraction rate which is approximately 6-10 kg ton^{-1} DM for fall harvests and 4-8 kg ton^{-1} for early spring harvests (Samson, pers. comm.). Lighter soils have about 25% higher N requirements.

Most studies on phosphate fertilisation report that switchgrass does not show a response to P-fertilisation even if soil values are low (Jung et al., 1990; Jung et al., 1988; Ocumpaugh et al., 1997).

During the growing season nutrient concentration of switchgrass declines. Calcium and Mg concentrations do not change much, while K, P and total ash will decline significantly (Parrish et al., 1997; Sanderson and Wolf, 1995). Allowing switchgrass to reach maturity will minimise concentrations of inorganic elements. This increases quality of the biomass for combustion and other uses. Jung el al. (1988, 1990) found that switchgrass will tolerate soils with much lower mineral levels than C_3 grasses, making lower soil mineral recommendations possible. Parrish et al. (1997) concluded that high yields can be produced from soils with low to medium soil test nutrient levels and that fertiliser application needs to be based on management systems rather than yield.

Diseases

Diseases and insect plagues are generally not a problem in new or established stands since most cultivars are genetically diverse and have significant levels of resistance (Moser and Vogel., 1995; Samson, pers. comm.; Wolf and Fiske, 1995). Varieties adapted to dry areas like the Great Plains will often develop more foliar disease problems (rusts) when grown in humid places (Moser and Vogel, 1995). Disease pressure is most severe where overnight dew occurs. Few specific diseases of switchgrass are discussed in the literature. Spot blotch (*Helminthosporium sativum* L.) has been studied (Zeiders, 1984). Moser and Vogel (1995) mention that lowland types are generally more resistant to rusts (*Puccinia* spp.) than upland types.
In young seedlings damping off diseases and insect predation may be a problem (Wolf and Fiske, 1995). In the first year seedling establishment can be improved with the use of insecticides (McKenna et al., 1991; Parrish et al., 1997). Switchgrass is susceptible to the maize streak monogeminivirus, panicum mosaic satellivirus and Panicum mosaic sobemovirus (Brunt et al., 1996).

Mycorrhizae

Hetrick et al. (1988) showed that several warm season (C_4) prairie grasses, among them switchgrass, inoculated with the mycorrhizal fungus *Glomus etunicatum* Becker and Gerd. yielded much more compared to non-inoculated grasses. Koslowsky and Boerner (1989) found that switchgrass inoculated with vesicular-arbuscular mycorrhizae (VAM) outgrew non-VAM plants at medium and low levels of soil Aluminium. Brejda et al. (1993) showed that switchgrass is highly mycorrhizal dependent on sandy soils and concluded that establishment on eroded sites may be greatly improved by inoculation with mycorrhizae. Vogel et al. (1997) found that in greenhouse studies mycorrhizae significantly improved switchgrass growth demonstrating that switchgrass is a mycorrhizae dependent species. In field studies inoculation of switchgrass seedlings with VAM had no significant effect on growth. It was concluded that indigenous mycorrhizae are effective with switchgrass and that inoculation of fields with mycorrhizae for switchgrass biomass production will not be needed.

In how far the lack of specific mycorrhizae at European experimental sites will play a role is not known. It seems that many different mycorrhizae can inoculate switchgrass.

Soil carbon

The use of energy crops and renewable materials contribute to reductions of CO_2 emissions, which is one of the main reasons for the interest in this subject. It is therefore important to quantify the total contribution of switchgrass to the CO_2 balance. Apart from the storage of carbon in the aboveground biomass, storage of carbon in the soil can play an important role.

Parrish et al. (1997) quantified the root mass in the top 30 cm of the soil profile under switchgrass crops in the upper southeast of the USA. The root mass varied greatly (2,7 to 18,6 Mg ha^{-1}) with an average rootmass of 8,2 Mg ha^{-1}. This was generally much higher than of tall fescue (*Festuca arundinacea*) a C_3 grass. Roots were also much more abundant deeper in the soil when compared to tall fescue. Zan et al. (1997) found that corn (*Zea mays*) produced higher above ground yields (16,2 Mg ha^{-1}) compared to switchgrass (14,2 Mg ha^{-1}) but corn had much less below-ground biomass (1,6 Mg ha^{-1}) compared to switchgrass (7,2 Mg ha^{-1}). Ocumpaugh et al.(1997) found that in Texas the average soil carbon levels increased from 10 to more than 12 g kg^{-1} after 3 years of switchgrass cover. Wullschlager et al. (1997) calculated a soil organic matter turnover time of 26 to 44 years under long-term switchgrass plantings in Tennessee.

Harvest

Harvesting of switchgrass can be done with conventional grass harvesting machines (Christian and Elbersen, 1998). In Europe switchgrass should probably be harvested in the winter when stems have dried out sufficiently. The thin woody stems of switchgrass allow good dry down in the winter. This may increase the harvest window of switchgrass compared to a crop like Miscanthus, which has thicker stems which would be expected to dry down slower. At Rothamsted moisture content at harvest was down to 30%, which may allow the baled crop to be stored for a short period before use, without the need for drying (Christian and Elbersen, 1998). Lower moisture contents may be possible in some parts of Europe where the continental climate gives drier winters.

Harvest and transport management of switchgrass has a large influence on energy conversion quality of switchgrass. Contamination of switchgrass samples with dirt during harvest and storage can increase alkali and ash content considerably (McLaughlin et al., 1996). Lodging can also complicate harvest and decrease quality due to higher moisture content and soil contamination.

The high C/N ratio of switchgrass biomass may make it possible to bale switchgrass at moisture levels of up to 20%, as has been found for ryegrass straw (Nay, 1996??).

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Table 1. Switchgrass varieties and their ecotype, ploidy level and area of origin and adaptation.

Variety	Ecotype	Ploidy level	Origin » latitude	Maturity	100 seed wt., mg	Comments	References
Alamo	lowland	Tetraploid	south Texas≈27.00	very late	94	Up to 2.5 m high, course, late flowering, >630 mm rain,	Alderson and Sharp, 1993; Anonymous. 1979; Gunter et al., 1996; Hopkins et al., 1996.
Blackwell	upland	Octoploid	northern Oklahoma ≈36.70	mid/ late	142	disease resistant, heavy stems, medium height, 380-760 mm, also in lowland, sandy areas	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996, Hopkins et al., 1995a.
Caddo	upland	Octoploid	central Oklahoma ≈34.80	late	159	Plants tall, robust, high seed production, forage yield under irrigation outstanding. Excellent seedling vigour, resistant to leaf rust.	Alderson and Sharp, 1993; Gunter et al., 1996; Hein, 1958; Hopkins et al., 1996
Carthage=NJ-50	?	?	North Carolina ≈36.00	late	148		Alderson and Sharp, 1993; Stout et al., 1988; Jung et al., 1990.
Cave-in-rock	upland/ lowland	Octoploid	southern Illinois ≈38.30	min/late	166	Medium to coarse. Resistant to zonate leafspot and rust, good in humid conditions. 1.5 m tall, well drained soils, moderate seedling vigour, coarser than Pathfinder and Blackwell	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996;George and Reigh, 1987.
Dacotah	upland	Tetraploid?	North Dakota ≈46.30	very early	148	Adequate forage and higher latitude of adaptation, short, early maturing.	Alderson and Sharp, 1993; Barker et al., 1990; Gunter et al., 1996.
Falcon	?	?			165		
Forestburg	upland	Tetraploid?	South Dakota ≈44.20	early	146	Forage yield high. very winter hardy, persistent, early,	Alderson and Sharp, 1993; Barker et al., 1988; Gunter et al. 1996;
Grenville	?	?			188	collected at 1800m, low rain, fine stemmed	Alderson and Sharp, 1993.
Kanlow	lowland	Tetraploid	central Oklahoma ≈34.80	very late	85	Tall, coarse, poorly drained soils, wide adaptation, not drought tolerant, slow establishment	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996; Hopkins et al., 1995a.

KY 1625	mixed	Octoploid?	West Virginia ≈39.00	mid	143	Fine stems, leafy, late maturity, poor seed quality.	Alderson and Sharp, 1993; Henry and Taylor, 1989; Hopkins et al., 1996.
Miami	?	Tetraploid	southern Florida ≈27.00	very late		Increased vegetatively	Gunter et al., 1996; Hopkins et al., 1996.
Nebraska 28	upland	?	northern Nebraska ≈42.60	early / mid	162	Well adapted to diverse soils. Susceptible to rust in areas with longer season than Nebraska. Used for forage and stabilization. semi decumbent, fine stems,	Alderson and Sharp, 1993. Hopkins et al., 1995a.
NL 93-1	lowland	?	36-40, 223 days to heading		121	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
NL 93-2	lowland	?	36-40, 223 days to heading		89	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
NU 94-2	upland	?	36-40, 210 days to heading		173	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
Pangburn	?	Tetraploid	Arkansas		96		Hopkins et al., 1996
Pathfinder	upland	Octoploid	Nebraska / Kansas ≈39.90	mid / late	187	good establishment, vigorous, winter hardy, leafy, rust resistant	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996; Newel, 1968.
PMT-279	lowland	Tetraploid	southern Texas ≈29.00				Gunter et al., 1996; Hopkins et al., 1996
REAP 921	upland	Tetraploid	south Nebraska	early / mid	90	resistant to lodging in Canada, small seeded, somewhat slow to establish	Samson pers. comm.
Shawnee	upland	Octoploid	South Illinois ≈38.30	mid / late		Cave-in-Rock is base, high IVDMD	Vogel et al., 1996;
Shelter=NY4006	mixed?	Octoploid?	West Virginia ≈41.70	mid	179	Upright, stiff, thicker stems, fewer leaves, lower seedling vigour, 7-10 days earlier then Blackwell,	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996.

Stuart	?	Tetraploid	Florida ≈28.50	late		Increased vegetatively	Hopkins et al., 1996
SL 93-2	lowland	Tetraploid?	26-30, 231 days to heading		87	Developed at OSU by Taliaferro and Hopkins derived from Alamo and related germplasms	Taliaferro and Hopkins, 1997
SL 93-3	lowland	Tetraploid?	26-30, 234 days to heading		100	Developed at OSU by Taliaferro and Hopkins derived from Alamo and related germplasms	Taliaferro and Hopkins, 1997
SL 94-1	lowland	Tetraploid?	26-30, 233 days to heading		91	Developed at OSU by Taliaferro and Hopkins derived from Alamo and related germplasms	Taliaferro and Hopkins, 1997
SU 94-1	upland		32-34 south central Oklahoma		183	Developed at OSU by Taliaferro and Hopkins	Taliaferro and Hopkins, 1997
Summer	upland	Tetraploid	south Nebraska ≈ 40.80	late/ mid	113.5	mostly rust resistant, tall for north, upright, coarse leaves, high yield of forage and seed.	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996.
Sunburst	upland	?	South Dakota ≈ 43.80	mid	198	Winter hardy, leafy, and heavy-seeded, good seedling vigour. Anthesis early August in eastern SD.	Gunter et al., 1996; Hopkins et al., 1995a.
Trailblazer	upland	Octoploid	Nebraska ≈ 40.00	mid	185	High IVDMD, compare to Pathfinder	Alderson and Sharp, 1993; Gunter et al., 1996; Hopkins et al., 1996; Vogel et al., 1991.
Wabasso	lowland	Tetraploid	southern Florida ≈27.00	very late		Increased vegetatively	Hopkins et al., 1996.
9005439	upland		wheatland Wyoming		183	Northern, tall, leafy, dark green, disease resistant,	pers comm. Connie Reynolds NRCS-PMC
9005438	lowland		Wyoming	later	177	Southern, light green, leafy, tall, high production	pers comm. Connie Reynolds

Table 2. Herbicides used in switchgrass.

Official name*	Other names	Action	When?	Available?	Problems	Reference
Atrazine	In Laddock	inhibits photo system A	pre-emergence/ post emergence	Not in Germany or Italy	Can hurt seedlings, especially lowland types. Use when seedlings have 5 leaves. Use low doses; 800 g/ha. Generally reduces seedling numbers and DW if used preplant. in Alamo less problems if foliar applied	Samson pers. comm.; Vassey et al., 1985; Moser and Vogel, 1995; Vogel, 1987; Martin et al., 1982; Sledge and Walker, 1993
Bensulide			pre-plant incorporated	Not in NL?	Generally reduces seedling numbers and DW	Bransby et al., 1997; Samson pers. comm.; Bovey and Hussey, 1991; Sledge and Walker, 1993
Bentazon	Basagran	inhibits photo system B	pre-emergence	OK in NL	Good against dicots. Used in Canada, safe for C4 grasses	Samson pers. comm. Rotteveel pers. comm.
Bromoxynil		inhibits photo system B		OK in NL	Against dicots in establishment year and in mature stand. can injure seedlings in warm weather.	Rotteveel pers. comm. Christian pers. comm.
Butylate				Not in NL		Samson, pers. comm.
Chlorsulfuron	Glean		pre-emergence/ post-emergence	Not in NL?	pre-emergence tolerated 0.006 lb/A post-emergence excessive injury	Samson pers. comm. Chenault and Wiese, 1988 Bovey and Hussey, 1991
Dicamba	Banvel	hormone			Too harsh! It should only be used in cloudy weather larger seedlings	Samson pers. comm. Rotteveel pers. comm. Ocumpaugh, 1997
Fluroxypyr?	Starane	hormone		Not in USA?	Can injure seedlings? Against broadleaf weeds - against monocots-	Rotteveel pers. comm. Christian pers. comm.
Glyphosate	Roundup	inhibits aminoacid synthesis B			More effective (aggressive) than paraquat.	Rotteveel pers. comm. Wolf and Fiske, 1995
Imazameth	Plateau	inhibits acetohydroxyacid synthase	pre-emergence	New in USA. Not available in Europe?	New in USA, switchgrass is tolerant	Samson pers. comm. Vogel et al., 1996
Imazethapyr	Pursuit		pre-emergence	Not in NL?	Generally reduces seedling numbers and DW(pre-emerg.) Postemerge it is better tolerated	Wilson, 1995; Samson pers. comm Sledge and Walker, 1993
Ioxynil		inhibits photo system B			against dicots in July of establishment year and	Christian, pers. comm.

					in mature stands	
Isoproturon?		inhibits photo system B		Not in USA?		Christian, pers. comm.
MCPA		Hormone			Against dicots not too strong, safe	Rottevell pers. comm.
Mecoprop-P		Hormone			against dicots	Christan pers. comm.
Metsulfuron-methyl	Ally	inhibits ALS	post-emergence/ pre-emergence		post-emergence good tolerance (0.02 kg/ha) or injury (0.004 lb/A). pre-emergence tolerance (0.006 lb/A)	Chenault and Wiese, 1988; Bransby et al., 1997; Samson pers. comm; Sledge and Walker, 1993
MSMA			post-emergence	Not in NL	Good tolerance, 2.24 kg/ha, with 2,4-D can damage switchgrass	Sledge and Walker, 1993 Bransby et al., 1997 Chenault and Wiese, 1988
Paraquat	Gramoxone	Inhibits photo system C	before planting or regrowth		Before emergence in mature stand	Christan pers. comm.
Simazine		inhibits photo system A	pre-emergence		Can damage switchgrass seedlings? will be phased out?	Christian and Elbersen, 1998
2,4-D		hormone	post-emergence		Generally hurt seedlings! or can hurt seedlings, use as late as possible	Samson pers. comm.; Bovey and Hussey, 1991; Sledge and Walker, 1993; Ocumpaugh et al., 1997; Moser and Vogel, 1995

* Anon. 1997. Common & chemical names of herbicides. J. Prod.. Agric., 10(4):iv-vi.