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The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe

Iris Lewandowski[a,*], Jonathan M.O. Scurlock[b], Eva Lindvall[c], Myrsini Christou[d]

[a] *Department of Science, Technology and Society, Copernicus Institute for Sustainable Development and Innovation, Universiteit Utrecht, Padualaan 14, 3584 CH Utrecht, The Netherlands*

[b] *Environmental Sciences Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, TN 37831, USA*

[c] *Svalöf Weibull AB, Box 4097, 904 03 Umeä, Sweden*

[d] *Center for Renewable Energy Sources (CRES), 19th km. Marathonos Avenue, 190 09 Pikermi-Attikis, Greece*

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Abstract

Perennial grasses display many beneficial attributes as energy crops, and there has been increasing interest in their use in the US and Europe since the mid-1980s. In the US, the Herbaceous Energy Crops Research Program (HECP), funded by the US Department of Energy (DOE), was established in 1984. After evaluating 35 potential herbaceous crops of which 18 were perennial grasses it was concluded that switchgrass (*Panicum virgatum*) was the native perennial grass which showed the greatest potential. In 1991, the DOE's Bioenergy Feedstock Development Program (BFDP), which evolved from the HECP, decided to focus research on a "model" crop system and to concentrate research resources on switchgrass, in order to rapidly attain its maximal output as a biomass crop. In Europe, about 20 perennial grasses have been tested and four perennial rhizomatous grasses (PRG), namely miscanthus (*Miscanthus* spp.), reed canarygrass (*Phalaris arundinacea*), giant reed (*Arundo donax*) and switchgrass (*Panicum virgatum*) were chosen for more extensive research programs. Reed canarygrass and giant reed are grasses with the C_3 photosynthetic pathway, and are native to Europe. Miscanthus, which originated in Southeast Asia, and switchgrass, native to North America, are both C_4 grasses. These four grasses differ in their ecological/climatic demands, their yield potentials, biomass characteristics and crop management requirements. Efficient production of bioenergy from such perennial grasses requires the choice of the most appropriate grass species for the given ecological/climatic conditions. In temperate and warm regions, C_4 grasses outyield C_3 grasses due to their more efficient photosynthetic pathway. However, the further north perennial grasses are planted, the more likely cool season grasses are to yield more than warm season grasses. Low winter temperatures and short vegetation periods are major limits to the growth of C_4 grasses in northern Europe. With increasing temperatures towards central and southern Europe, the productivity of C_4 grasses and therefore their biomass yields and competitiveness increase.

Since breeding of and research on perennial rhizomatous grasses (PRG) is comparatively recent, there is still a significant need for further development. Some of the given limitations, like insufficient biomass quality or the need for adaption to certain ecological/climatic zones, may be overcome by breeding varieties especially for biomass production. Furthermore, sure and cost-effective establishment methods for some of the grasses, and effective crop production and harvest methods, have yet to be developed.

*Corresponding author. Tel.: +31-30-253-7640; fax: +31-30-253-7601.

E-mail addresses: i.lewandowski@chem.uu.nl (I. Lewandowski), jscurloc@utk.edu (J.M.O. Scurlock), eva.lindvall@swseed.se (E. Lindvall), mchrist@cres.gr (M. Christou).

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This review summarizes the experience with selecting perennial grasses for bioenergy production in both the US and Europe, and gives an overview of the characteristics and requirements of the four most investigated perennial rhizomatous grasses; switchgrass, miscanthus, reed canarygrass and giant reed.

Keywords: Perennial rhizomatous grasses; Switchgrass; Miscanthus; Reed canarygrass; Giant reed; Bioenergy

1. Introduction

Perennial grasses have been widely used as fodder crops for centuries, often contributing significantly to energy supply on farms through the use of draft animals. For example, as late as 1920 in the United States, 27 million animals provided traction power on farms and in cities, fuelled by some 35–40 million hectares of grasslands [1]. In the 21st century, perennial grasses may be set for a comeback through a number of different energy conversion pathways.

There has been increasing interest in the use of perennial grasses as energy crops in the US and Europe since the mid-1980s. The characteristics which make perennial grasses attractive for biomass production are their high yield potential, the high contents of lignin and cellulose of their biomass and their generally anticipated positive environmental impact.

Energy crops are crops which are produced with the express purpose of using their biomass energetically. High contents of lignin and cellulose in their biomass are desirable, especially when they are used as solid biofuels, for two main reasons. First they have a high heating value due to the high content of carbon in lignin (about 64%). Secondly strongly lignified crops can stand upright at low water contents. Therefore their biomass has lower water contents, the biomass can dry 'on the stem' and a late harvest for improved biomass quality is possible [2]. The biomass of perennial grasses has higher lignin and cellulose contents than the biomass of annual crops.

There are many ecological benefits expected from the production and use of perennial grasses. The substitution of fossil fuels or of raw materials based on fossil fuels by biomass is an important contribution to reduce anthropogenic CO_2 emissions. Compared to other biomass sources, like woody crops and other C3 crops, C4 grasses may be able to provide more than twice the annual biomass yield in warm and temperate regions because of their more efficient photosynthetic pathway [3].

Unlike annual crops, the need for soil tillage in perennial grasses is limited to the year in which the crops are established. The ecological advantages of the long periods without tilling are reduced risk of soil erosion and a likely increase in soil carbon content [4,5]. Furthermore, due to the recycling of nutrients by their rhizome systems, perennial grasses have a low demand for nutrient inputs [6]. Since they have few natural pests, they may also be produced with little or no pesticide use [7].

Studies of fauna show that due to long-term lack of soil disturbance, the late harvest of the grasses in winter to early spring and the insecticide-free production, an increase of abundance and activity of different species, especially birds, mammals and insects, occurs in stands of perennial grasses [8,9]. Perennial grasses can therefore contribute to ecological values in agricultural production. They can also function as elements in landscape management and as habitat for different animals.

In both the US and in Europe, there are various candidate perennial grasses available which differ considerably in their potential productivity, chemical and physical properties of their biomass, environmental demands and crop management requirements. The initial question for biomass research with perennial grasses was to identify those grasses that best fulfill the demands of bioenergy production, namely high biomass yields and appropriate biomass characteristics.

The *aim* of this review is to summarize previous experience with selecting perennial grasses for bioenergy (i.e. energy from biomasss) production in both the US and Europe, and to give an overview of the characteristics and requirements of the four most investigated perennial rhizomatous grasses (switchgrass: *Panicum virgatum*, miscanthus: *Miscanthus* spp., reed canary grass: *Phalaris arundinacea* and giant reed: *Arundo donax*).

2. Selection of perennial grasses for bioenergy production in the US

In 1978 the US Department of Energy (DOE) established a program on bioenergy feedstock development beginning with the screening of tree species and the Short Rotation Woody Crops Program, starting 1979 at the Oak Ridge National Laboratory (ORNL). Since 1984, when the Herbaceous Energy Crops Research Program (HECP) was established, ORNL has provided management and field support for research on non-woody terrestrial plant species as energy crops that can be economically produced on a wide variety of sites and incorporated into conventional farming operations. Near-term objectives of maximising potential current economic yields have been combined with the longer-term objectives of improving and protecting yields through breeding and biotechnology. Initial work concentrated on herbaceous crop screening studies; at Geophyta in northern Ohio, Purdue University, Indiana, Virginia Polytechnic Institute and State University, and Auburn University, Alabama; and two later screening trials in the Great Plains region (Iowa State University and North Dakota State University). By the University of Florida the subtropical C_4 grasses elephantgrass (*Pennisetum purpureum*) and energy and sugar cane (*Saccharum* spp.) were screened [10]. The aims were to examine yield potential, biochemical composition and best management practices across a wide diversity of sites. After evaluating 35 potential herbaceous crops of which 18 were perennial grasses between 1985 and 1989 (Table 1), it was concluded that switchgrass was the perennial grass which showed the greatest potential [11]. In 1990 the HECP evolved into the Bioenergy Feedstock Development Program (BFDP).

In 1991, within BFDP it was decided to focus research on a “model” crop system and to concentrate research resources on a single perennial grass in order to rapidly attain its maximal output as a biomass crop. Switchgrass (*Panicum virgatum*) was chosen as the model crop for several reasons.

(1) Switchgrass is a native perennial warm-season (C_4) grass with deep roots, and has the capacity for high yields on relatively poor quality sites, where water and nutrient availability would prevent the successful production of conventional crops. A widely adapted endemic species, it is an important ecological component of North American native grassland ecosystems, occurring from Quebec to Mexico, and from prairies to brackish marshes and open woodlands. Switchgrass also shows considerable within-species variability in yield, suggesting likely gains through further breeding.

(2) Switchgrass combines more of the attributes desirable for bioenergy feedstock production than other grasses. These attributes include distribution and high productivity across a wide geographical range and on diverse agricultural sites around the US, high water use and nutrient use efficiency, and positive environmental attributes—including effects on soil quality and stability, cover value for wildlife, and relatively low inputs of energy, water and agrochemicals required per unit of energy produced [12].

(3) Some of the other perennial grasses showed major limitations to production. For example, Wright [13] reports on the screening of different perennial grasses on wet marginal soils in Ohio. Here, tall fescue, smooth bromegrass and reed canary grass had problems with initial establishment, while the species least affected by establishment failure were timothy and switchgrass. Parrish [14] also reported improved establishment of the C_4 grasses switchgrass and lovegrass compared with reed canarygrass. However, the yields of lovegrass decreased over several years in competition with tall-growing weeds, whereas switchgrass showed no such decline. Compared to C_3 grasses like tall fescue and reed canarygrass the yields of switchgrass are also less affected by drought [15].

(4) Switchgrass can easily be integrated into conventional farming operations because conventional equipment for seeding, crop management and harvesting can be used. Furthermore switchgrass can be harvested in one harvest per year. Although other C_4 grasses like weeping lovegrass showed a good yield potential (Table 1), Turhollow [15] reported that weeping lovegrass yielded an additional 1.6 t ha^{-1} yr^{-1} when harvested on two-cut cycle, compared with a single harvest. However, a single harvest for switchgrass may yield up to 0.7 t DM ha^{-1} more than two harvests (although this trend may be reversed for upland varieties, depending

Table 1
18 perennial grass species that were screened by the US herbaceous energy crops research program

English name	Latin name	Photo- synthetic pathway	Yields reported [t DM ha^{-1} a^{-1}][a]	Source
Crested wheatgrass	*Agropyron desertorum* (Fisch ex Link) Schult.	C_3	16.3	[121]
Redtop	*Agrostis gigantea* Roth	C_3	Not available	
Big bluestem	*Andropogon gerardii* Vitman	C_4	6.8–11.9	[11,121]
Smooth bromegrass	*Bromus inermis* Leyss.	C_3	3.3–6.7	[13]
Bermudagrass	*Cynodon dactylon* L.	C_4	1.0–1.9	[122]
Intermediate wheatgrass	*Elytrigia intermedia* [Host] Nevski	C_3	Not available	
Tall wheatgrass	*Elytrigia pontica* [Podp.] Holub	C_3	Not available	
Weeping lovegrass	*Eragrostis curvula* (Schrad.) Nees	C_4	6.8–13.7	[14]
Tall Fescue	*Festuca arundinacea* Schreb.	C_3	3.6–11.0	[13]
Switchgrass	*Panicum virgatum* L.	C_4	0.9–34.6	[123]
Western wheatgrass	*Pascopyrum smithii* (Rydb.) A. Love	C_3	Not available	
Bahiagrass	*Paspalum notatum* Flugge	C_4	Not available	
Napiergrass (elephant grass)	*Pennisetum purpureum* Schum	C_4	22.0–31.0	[15]
Reed canary grass	*Phalaris arundinacea* L.	C_3	1.6–12.2	[48]
Timothy	*Phleum pratense* L.	C_3	1.6-6.0	[13]
Energy cane	*Saccharum* spp.	C_4	32.5	[15]
Johnsongrass	*Sorghum halepense* (L.) Pers.	C_4	14.0–17.0	[15]
Eastern gammagrass	*Tripsacum dactyloides* (L.) L.	C_4	3.1–8.0	[123]

[a]t = Mg.

upon latitude). Switchgrass therefore has the advantage of concentrating the yield in one harvest. It also has the flexibility to be utilized both as a bioenergy species and as a forage crop. The use as the latter, however, requires that switchgrass is grazed before seedstalks develop for obtaining good forage quality and palatibility [16].

(5) The tall tropical perennial grasses energy cane and napiergrass have yielded well in limited trials at Auburn, Alabama, and in the subtropical Lower South [10]. However, an important consideration for thick-stemmed species such as sorghum, energy cane and napiergrass is that harvest, handling and storage methods require forage harvesting equipment, whereas thin-stemmed herbaceous energy crops may be harvested with more conventional haying equipment [15]. Thin-stemmed species also demonstrate faster self-drying in the field, enabling greater advantage to be taken of the reduction in moisture content with only a modest delay in harvest.

A series of six research projects was initiated by DOE through the BFDP in 1992 to gain new information on the yield potential of switchgrass as a bioenergy crop. These projects are evaluating the most promising existing varieties of switchgrass in regional field trials (Virginia Polytechnic Institute, D. Parrish; Auburn University, D. Bransby; Texas A& M University, M. Sanderson), perform breeding to search for new improved varieties (Oklahoma State University, C. Talliaferro), do physiology work to develop indicators for selection and evaluation of superior plant growth potential (ORNL, S. Wullschleger) and develop tissue culture techniques for biotechnological improvement (University of Tennessee, B. Conger). Some US research work continues on other high-potential herbaceous energy crop species such as napier grass, bermuda grass and bahia grass in the US southeast (Gordon Prine, pers. comm., University Florida, Gainesville).

3. Research on perennial grasses as bioenergy crops in Europe

European research on perennial grasses for bioenergy production began with the interest shown in miscanthus, which was introduced as ornamental plant about 50 years ago. The first experiments on growing miscanthus for pulp and energy were carried out in Denmark in the late 1960s and the first experimental field was established in 1983 [17]. Based upon promising preliminary results, a research project funded under the European JOULE program was initiated in 1989. Field trials were established in Denmark, Germany, Ireland and the UK to investigate the biomass potential of *M.* × *giganteus* across northern Europe. In 1993, a larger project was set up under the European AIR program, which extended the distribution of field trials into southern Europe, including Greece, Italy and Spain [18]. Nationally funded projects in Denmark, Netherlands, Germany, Austria and Switzerland supported research on propagation and establishment, management practices, harvest and handling of miscanthus. In 1997, under the European FAIR program, a project for the development of new miscanthus hybrids, breeding methods for miscanthus and the screening of different genotypes all over Europe was funded.

Miscanthus shows very vigorous growth, and its biomass can be harvested in one cut in a delayed harvest system, allowing it to dry out. Major limitations that were identified for the production of miscanthus are:

(a) A narrow genetic base: There was only one genotype available in Europe in the 1990s, *Miscanthus* × *giganteus*, which was productive enough to be considered as a bioenergy crop. For the development of miscanthus a broader genetic base was needed in order to have enough adapted varieties for different site conditions in Europe and to prevent the spread of pests and diseases.

(b) Poor overwintering in northern Europe: In different areas of Germany, Denmark and Ireland substantial overwinter losses of *Miscanthus* × *giganteus* occurred during the first year after planting [19].

(c) The need to propagate miscanthus vegetatively causes high establishment costs: *Miscanthus* × *giganteus* is a self-sterile triploid hybrid which does not form fertile seeds. Propagation therefore is performed by micropropagation or by rhizome cutting. Prices for establishment are about 3000–6000 Euro per hectare [7].

Given the limitations of miscanthus, it seemed to be worth while to search for other perennial grasses which can be established by seeding at lower costs and that are more adapted to the climatic conditions at the different sites in Europe. Indigenous C_3 grasses like common reed, cordgrass and tall fescue have been evaluated at various central and northern European sites [20–22]. Table 2 gives an overview of perennial grasses being tested in Europe as energy crops.

Among those indigenous grasses which are characterized by regionally high biomass yields and which seem to offer good bioenergy characteristics are found giant reed (*Arundo donax*) for the Mediterranean areas, and reed canarygrass (*Phalaris arundinacea*) for northern Europe. During the 1980s several projects were initiated in Sweden to evaluate different crops and their biomass potential. Reed canary grass was chosen as one of the most interesting crops for energy and material use and further investigations were performed on its production system, harvest techniques and biomass quality [23]. Over the past 10 years, reed canarygrass breeding for industrial use has been carried out in Sweden and Finland [24]. Starting in 1993, the performance of different reed canarygrass varieties in various northern European countries was evaluated in an EU project, and the feasibility of using reed canarygrass as solid biofuel was demonstrated. Systematic research on the performance of giant reed as an energy crop and its appropriate cultivation techniques began only in recent years. The European "Giant reed (*Arundo donax* L.) Network" has been established since January 1997, under the framework of the FAIR Program, aiming to generate information on the ability of this plant to be introduced into EU agriculture for energy and pulp production.

Until recently, switchgrass was known in Europe only as an ornamental grass. However, since 1988, small field trials (up to 2.5 ha) have been performed, mostly within the EU-funded switchgrass productivity network. Under this project, more than 20 varieties have been tested under European conditions [25]. Switchgrass was chosen because the US experience showed that it is a promising bioenergy crop and a broad range of different varieties are available. The advantage of switchgrass is that it can be introduced into Europe as a highly productive C_4 grass that can be established by seeding.

Table 2
Perennial grasses grown or tested as energy crops in Europe

Common English name	Latin name	Photo-synthetic pathway	Yields reported [t DM $ha^{-1}a^{-1}$][a]	Citation
Meadow Foxtail	*Alopecurus pratensis* L.	C_3	6–13	[20]
Big Bluestem	*Andropogon gerardii* Vitman	C_4	8–15	(unpublished results)
Giant Reed	*Arundo donax* L.	C_3	3–37	[124]
Cypergras, Galingale	*Cyperus longus* L.	C_4	4–19	[125]
Cocksfoot grass	*Dactylis glomerata* L.	C_3	8–10	[126]
Tall Fescue	*Festuca arundinacea* Schreb.	C_3	8–14	[22]
Raygras	*Lolium* ssp.	C_3	9–12	[22]
Miscanthus	*Miscanthus* spp.	C_4	5–44	[7]
Switchgrass	*Panicum virgatum* L.	C_4	5–23	[25]
Napier Grass	*Pennisetum purpureum* Schum	C_4	27	[127]
Reed canary grass	*Phalaris arundinacea* L.	C_3	7–13	[128]
Timothy	*Phleum pratense* L.	C_3	9–18	[20]
Common Reed	*Phragmites communis* Trin.	C_3	9–13	[129]
Energy cane	*Saccharum officinarum* L.	C_4	27	[127]
Giant Cordgrass/ Salt Reedgrass	*Spartina cynosuroides* L.	C_4	9 5–20	[125,45]
Prairie Cordgrass	*Spartina pectinata* Bosc.	C_4	4–18	[125]

[a]t = Mg.

Many of the of the C_3 grasses being tested showed limitations such as:

- lower yields compared to the C_4 grasses. Many C_4 grasses have a higher water use efficiency (WUE), about twice that of C_3 crops [26,27]. However, this is not the case for very cool regions where temperature limits the photosynthetic process—such as Sweden or Finland—and C_3 grasses perform better.
- high yields can only be obtained with multiple cutting systems and with high nitrogen input [22,28,29].
- delayed harvest is not possible due to lodging of grasses. This is mainly true for the fodder grasses which are bred for a multiple cutting system and high leafiness, with thin stems that do not lignify quickly. This is not true for giant reed and reed canarygrass, which can be harvested with a one-cut system.

Mostly funded by the European Commission, research on perennial grasses as bioenergy crops in Europe is concentrated on the following four rhizomatous grasses:

I. Reed canarygrass for northern Europe, where it displays the following advantages:

- it is an indigenous crop, already adapted to the site conditions;
- it is adapted to short vegetation periods and low temperatures;
- seed establishment is possible;
- overwintering is safe;
- it can be harvested once a year during late fall to early spring, and delayed harvest is possible;
- the biomass has good combustion quality and, compared to hardwood, good fibre quality;
- it has broad genetic variability.

II. Miscanthus for central and southern Europe, where it has the following advantages:

- a high biomass yield potential;
- high nutrient and water use efficiency (due to C_4 photosynthetic pathway);
- good combustion qualities of the biomass;
- it can be harvested once a year during late fall to early spring, and delayed harvest is possible;
- high persistence;

Table 3
Comparison of physiological properties and ecological demands of the main perennial rhizomatous grasses

	Switchgrass	Miscanthus	Giant reed	Reed canary grass
Latin name	*Panicum virgatum*	*Miscanthus* ssp.	*Arundo donax*	*Phalaris arundinacea*
Family	Subfamily *Panicoideae* of the *Gramineae* (*Poaceae*) family	Subfamily *Andropogoneae* of the *Gramineae* (*Poaceae*) family	Subfamily *Arundinoideae* of the *Gramineae* (*Poaceae*) family	Subfamily *Pooideae* of the *Gramineae* (*Poaceae*) family
Photosynthetic pathway	C_4	C_4	C_3	C_3
Soils	Wide range	Wide range	Wide range	Wide range
pH	4.9– 7.6			
Water supply	Drought tolerant, moderately tolerant of flooding, but does not grow well in wet areas	Not tolerant to stagnant water and prolonged drought periods, No soil compaction	Prefers well drained soils with good water supply, but grows heavy clays to loose sands and gravelly soils, also on saline soils.	Drought tolerant, Tolerant to wet areas
Daylength	Short day plant	Long day plant	No information available	Long day plant

- broad genetic variability in regions of origin which can be used as basis for breeding.

III. Switchgrass for central and southern Europe, where it has the following advantages:

- seed establishment possible;
- high biomass yield potential;
- high nutrient and water use efficiency (due to C_4 photosynthetic pathway);
- good combustion qualities of the biomass;
- it can be harvested once a year during late fall to early spring, and delayed harvest is possible;
- experience and genetic variability available from the US can be used;

IV. Giant Reed for the Mediterranean region, where it has the following advantages:

- indigenous crop, already adapted to the site conditions;
- high biomass yields;
- it can be harvested once a year during late fall to early spring, and delayed harvest is possible;
- low irrigation and nitrogen inputs;
- high resistance to drought;
- genetic variability available in Southern Europe (although it is not anticipated to be broad as the seed set of the crop is poor).

So far no field trials have been performed in Europe which compare the major perennial rhizomatous grasses at one site. However, from the various field trials that were performed, conclusions can be drawn about the demands of the grasses and their suitability for different sites.

The following section describes the physiology, demands and potentials of the four most important perennial rhizomatous grasses for bioenergy production being investigated in the US and Europe (Table 3).

4. Description of the main perennial rhizomatous grasses for the US and Europe

4.1. Switchgrass

4.1.1. Origin

Switchgrass belongs to the subfamily *Panicoideae* of the *Gramineae* family. It is native to North America where it occurs naturally from 55°N latitude to central Mexico. It is one of the grasses that dominated the North American tall-grass prairie. Although generally associated with the natural vegetation of Great Plains and the western Corn Belt it occurs widely in grasslands and non-forested areas throughout North America east of the Rocky Mountains and south of 55°N [30]. Switchgrass has been seeded in pasture and range grass mixtures in the Great Plains over the past 50 years, and has become increasingly important as a pasture grass in the central and eastern US because of its ability to be productive during the hot months of summer, when cool-season grasses are less productive [30].

4.1.2. Physiology

Switchgrass is a tall perennial C_4 grass. In southern parts of the US, switchgrass can grow to more than 3 m height and develop roots to a depth of more than 3.5 m [31]. It has short rhizomes and the stand has the potential to form a sod. Most tillers produce a seedhead when moisture is adequate. The inflorescence is a diffuse panicle, 15–55 cm long, with spikelets at the end of long branches. Spikelets are two-flowered with the second floret being fertile and the first one sterile or staminate [30]. The seed weight of switchgrass is about 389,000 seeds per pound for most varieties and 427,365 for Alamo [32]. The expected life of a pasture would be 10 years or more if properly managed.

4.1.3. Genetic background and availability of varieties

Switchgrass is a cross-pollinated plant that is largely self-incompatible. It has a basic chromosome number of nine. Most switchgrass cultivars are tetraploid or hexaploid [33]. Plants of the same ploidy level can usually be intercrossed regardless of ecotype [34].

Switchgrasses are divided into upland and lowland ecotypes. The upland ecotypes are most commonly octaploids ($2n = 8x = 72$) or occasionally hexaploids ($2n = 6x = 54$). They are shorter, fine-stemmed and are more adapted to drier habitats [35]. The lowland ecotypes are predominantly tetraploid ($2n = 4x = 36$), coarse-stemmed and tall growing, more robust and more resistant to rust (*Puccinia graminis*). They have a more bunchy-type growth and are more adapted to wetter sites, being found on floodplains [30,35]. Lowland ecotypes are later-maturing than upland ecotypes and therefore require a longer growth period [35]. Breeding work first began on switchgrass in the Great Plains during the 1930s [30]. Formerly, breeding was aimed at producing varieties for fodder. Nowadays breeding is performed for the production of varieties suitable for bioenergy production, too (see [36]).

Moser and Vogel [30] give an overview on the principle cultivars of switchgrass available. Due to their high yields for bioenergy production the most promising cultivars are 'Alamo' for the deep South, 'Kanlow' for mid-latitudes and 'Cave-in-rock' for the central and northern States [37]. Kanlow and Alamo are lowland ecotypes while Cave-in-rock is an upland ecotype. All of them are late-maturing, which ensures production into early Fall (Autumn) and therefore higher biomass yields. Alamo and Kanlow mature later than Cave-in-rock [38].

4.1.4. Ecological demands

Switchgrass does well on a wide variety of soil types. It is drought tolerant and produces well on shallow rocky soils. At the same time it is also tolerant to wet areas. It can grow on sand to clay loam soils and tolerates soils with pH values ranging from 4.9 to 7.6 [39]. Cave-in-rock is more adapted to the growing conditions in high humidity areas. Kanlow is more drought tolerant than Alamo and Cave-in-rock.

Temperature. Switchgrass germinates very slowly when the soil temperature is below 15.5°C. Most seedlings will germinate after three days at 29.5°C [39]. According to Hsu [40] the minimum temperature for switchgrass germination is 10.3°C. Artificial freeze tests with two populations of switchgrass showed a LT50 (lethal temperature at which 50% are killed) value of −4°C prior to the onset of cold hardening. Slow cold-hardening increased the cold tolerance to −18°C within one month [41]. Seed dormancy can be a problem and can be broken by cold stratification (see below).

Photoperiod. Switchgrass requires short days (< 10 h) to initiate flowering [42]. The photoperiod response is linked to winter survival. Southern types of switchgrass from Texas and Oklahoma moved too far north will not consistently survive the winters because they continue growth too late in the fall and do not winter harden properly [30]. These grasses should not be moved more than 500 km north.

4.1.5. Biomass yields

Within the Bioenergy Feedstock Development Program at Oak Ridge National Laboratory, nine switchgrass cultivars were evaluated across a network of 19 research blocks (plot sizes 1.5×6.1 m, 4 replications). Annual yields of the best varieties have averaged about 16 t DM ha^{-1} across all plots, with yields in excess of 22 t DM ha^{-1} occurring at the best plots. The highest yielding varieties were the lowland varieties Alamo and Kanlow at southern and Mid-Atlantic sites, while the upland variety Cave-in-rock performed best in the northern central plains [43].

Stands are typically not harvested during the first growing season, reach two-thirds of their capacity during the second year, attaining full yield in the third [37].

The highest yields per hectare can be obtained when switchgrass is harvested once or twice per year. The one or two-cut systems provide often similar average yields [43].

4.1.6. Biomass characteristics

Characteristics of switchgrass biomass are listed in Table 4. Of the eight switchgrass genotypes compared by Sladden [38], the six upland types did not vary much in their biomass composition because they were all cut at the same maturity. Alamo and Kanlow had significantly lower nitrogen (N) contents and higher fiber contents which was related to the later harvest date at maturity rather than differences in nutrient partitioning [44]. In the same trial the biomass quality was influenced by harvest date. Harvest in June/July was compared to harvest in August/September. With a 2 month later harvest the N content decreased for all early maturing varieties, but an increase of N was recorded for the late maturing Alamo and Kanlow. For most varieties an increase in ash content was recorded with later harvest [44]. Other trials, however, showed that later-harvested switchgrass biomass had lower ash and potassium (K) contents [45]. The N contents was higher for the summer harvest of the two-cut system and lowest in the fall harvest of the one-cut system [46] and a clear decrease of ash contents with progressed maturity was observed [37]. The total N withdrawal by the biomass in a two-cut system varied from 90 to 144 kg ha^{-1} yr^{-1} over 5 years of measurements, while only a total of 31–63 kg N ha^{-1} yr^{-1} was withdrawn in the one-cut fall harvest system.

4.1.7. Management of switchgrass as a bioenergy crop

The management issues with the greatest impact on utilization of switchgrass as a bioenergy crop are establishment, the timing and frequency of harvests, and nitrogen and fertilization strategies [43].

Establishment. All over the US, switchgrass is established by seeding. Stand failure as a result of poor seed quality, weed competition, and seedling physiology will have major implications on the cost of switchgrass biomass. Switchgrass often has a high degree of dormant seed when harvested. This dormancy can be broken when the seed is stored for 2–4 years in a warm place or when exposed to cold–wet conditions (stratification). Stratification can occur during the winter in the field, and adequate cold–wet conditions may occur if the field is planted between late winter and the beginning of May. However, weed competition may become too strong at the same time [39]. If germination is low, a wet–chill treatment may be required. Soaked seeds are stored for draining for 24 h in a cool place and then in the refrigerator at about 3.5–5.5°C for 4 weeks. A firm seedbed, proper planting depth, and good weed control during the first year are very important to good switchgrass establishment [39].

Switchgrass can be drilled in a conventional seedbed or by no-till seeding methods. For seeding in a conventional seedbed the field operations that are typically used for small seeded forages can be applied. The soil has to be firm at planting. Seeds can be broadcast or drilled in rows. As light-seeded species they should not be placed deeper than 1–2 cm [30]. Cultipacking after drill planting is recommended to have a good seed–soil contact. For no-till planting, the soil surface should be rather dry and seeds should be sown at 0.5–1.3 cm depth. When no-till planting is applied soil moisture is of less concern than with conventional seeding. For no-till planting less seed (9 kg ha^{-1}) is necessary than for conventional seeding (11 kg ha^{-1})

Table 4
Biomass yields and biomass characteristics reported for the main perennial rhizomatous grasses

	Switchgrass	Miscanthus	Giant reed	Reed canary grass
Yields in t[a] DM $ha^{-1}a^{-1}$	Yields for varieties Alamo: 13.2 (Texas) 12.2 (Upper South) 26.0 (Alabama) 34.6 (two cut system, Alabama) Kanlow: 10.1 (Texas) 12.4 (Upper South) 18.5 (Alabama) 23.2 (two cut system, Alabama) 11.1 (3rd–6th year, Britain) Cave-in-rock: 5.4 (Texas) 9.4 (Upper South) 9.5 (Alabama) 10.4 (two cut system, Alabama) 10.6 (3rd–6th year, Britain)	Denmark: 5–15 Germany: 4–30 Britan: 10–15 Switzerland: 13–19 Austria: 22 Spain: 14–34 Greece: 26–44 Turkey: 28 Italy: 30–32	South Greece: 7–31 North Greece: 5–17 Spain: 8–37 South Italy: 15–34 North Italy: 3–32 Germany: 15–20	Finland, Sweden: 5–12 Britain: 6–12
Moisture content at harvest	15	16–62		10–23
Ash (% of DM)	4.5–10.5	1.6–4.0	4.8–7.8	1.9–11.5
N (% of DM)	0.71–1.37	0.19–0.67	0.2–0.4	0.45–1.54
K (% of DM)		0.31–1.28		0.06–0.81
Ca (% of DM)	0.28–0.73	0.08–0.14		0.08–0.32
Cl (% of DM)		0.10–0.50		0.01–0.30
S (% of DM)	0.12	0.04–0.19		0.06– 0.11
Si (% of DM)				0.56–3.70
Heating value ($MJ\ kg^{-1}$)	17.0	17.1–9.2	14.8–18.8	16.6–19.3
Ash fusion temperature	1016	1020		1100–1650
Citation	[6,45,44]	[5,7,130]	[124]	[6,23,81,89]

[a]t = Mg.

[39]. According to Sladden [38] a row spacing of 80 cm can be recommended because this led to higher yields in the second and third year than row spacing of 20 cm.

Fertilizer and input demand. There are various reports that switchgrass shows no response to N fertilizer or only to the first 50 kg [15]. Above that level only moderate yield increases occurred. Economically viable yields will require fertilization rates between 50–100 kg ha^{-1} yr^{-1} [47]. The effect of N fertilizer, however, can be site specific. On locations in the southern US switchgrass can respond to N fertilizer levels up to 200 kg ha^{-1} [35]. On sites in Virginia 50 kg N ha^{-1} resulted in maximal biomass productivity. It was concluded by Wright [47] that N fertilization is effective only on poorer quality sites with typically little or no effects at levels above 70 kg ha^{-1} yr^{-1}. On more fertile sites, effects have typically been negative or neutral. N fertilizer should be given in late spring. If the soil tests indicate medium or higher P and K levels, no P and K fertilizer is needed at the time of planting. According to Wolf [39] N should not be applied at planting.

Weeds and diseases. Weeds can be a major obstacle for switchgrass establishment, especially summer annuals. They can be reduced by growing the appropriate crop the year before. One year prior to switchgrass planting the field should be plowed or chisel plowed [39]. Broadleaf weeds can be controlled with herbicides, e.g. light rates of 2,4-D. In the first year after seeding herbicide may still be necessary to control weeds. A reduction of weed competition can also be achieved by infrequent clipping at 6–9 cm [48].

If seedlings are slow to establish in the first year, the fields may be completely covered with weeds. However, experience from the Netherlands (Wolter Elbersen, pers. comm., ATO B.V. Wageningen) shows that the stand can recover in the second year, even if strong weed growth occurs in the first year.

For new seedlings of switchgrass grasshoppers, crickets, corn flea beetles and other insects can become a problem and an insecticide may be needed [39].

There are several diseases that can affect switchgrass like *Panicum* mosaic virus or various leaf rusts (*Puccinia* spp.). There are no economical or approved controls for these diseases [39].

Harvest frequency and time. In the US, trials have been performed to identify the optimal harvest frequencies and dates. In the Deep South, a two-cut system with harvests in July and October has provided somewhat higher yields under the longer southern growing season, whereas a single cut system may be more advantageous further north [12]. Yield data emphasize the regional specificity of optimum cutting practices. Dry matter yields with the two-cut system were only higher when there was adequate summer soil water [46,49]. It was concluded that the increase in yield may not justify the costs of added harvest [35]. Yields may be reduced by approximately 20% by harvesting after the first frost, but this can result in improved yields the following years and improved quality of the late harvested biomass due to reduced mineral content [12]. Allowing switchgrass to mature fully and to dry down before harvest results in nutrient translocation. Therefore, late harvesting removes lower levels of nutrients [47].

4.2. Miscanthus

4.2.1. Origin

According to Adati [50] and Deuter [51] the genus *Miscanthus* consists of 17 species and can be divided into four sections. The genetic origin of miscanthus is in East-Asia, where it is found throughout a wide climatic range from tropical and subtropical and warm temperate parts of Southeast Asia to the Pacific Islands [52].

The genotype widely used in Europe for productivity trials, *Miscanthus* × *giganteus*, was introduced from Japan to Denmark in 1930.

4.2.2. Physiology

Miscanthus is a C_4 grass with high radiation and water use efficiencies [21,53–55]. There are two general types of rhizomes. The species *Miscanthus sacchariflorus* has a broad creeping and thick stemmed rhizome while the *Miscanthus sinensis* rhizome is tuft forming and has thinner stems. Hybrids of them, like *Miscanthus* × *giganteus*, form an intermediate type of rhizome. The inflorescence is a fan-like panicle with a long axis and many racemes. Miscanthus is a wind pollinated genus [51]. The canopy of *Miscanthus* × *giganteus* can reach a height of 4 m.

Miscanthus is highly persistent; the oldest plantation in Europe is a 18 year old stand in Denmark. The estimated life time of a plantation is 20–25 years.

4.2.3. Genetic background and availability of varieties

Of the four sections of miscanthus—“Kariyasua”, “Diandra”, “Thiarrhena” and “Eumiscanthus”—only the latter two contain genotypes of interest for biomass production [51]. The basic chromosome number of miscanthus is 19. The triploid genotype *Miscanthus* × *giganteus* has 57 somatic chromosomes, and is probably a natural hybrid involving *Miscanthus sacchariflorus* (diploid, section Eumiscanthus) and *Miscanthus sinensis* (tetraploid, section Triarrhena) [52]. As a consequence of its triploidy, *M.* × *giganteus* is sterile and cannot form fertile seeds [56]. *Miscanthus* is self-incompatible. The two species of miscanthus that are of interest for breeding genotypes for bioenergy are *M. sacchariflorus* and *M. sinensis*. In its natural habitat, hybridization between miscanthus species often happens and leads to new forms. Interspecific hybrids are often more vigorous than the parental plants. *M. sacchariflorus* genotypes are more adapted to warmer climates, whereas *M. sinensis* genotypes are more winter hard [57,58]. The aim of miscanthus breeding for bioenergy is the production of hybrids that in some aspects are similar to *Miscanthus* × *giganteus*. Desirable characteristics include a high biomass yield potential and sterile seeds. Seed sterility of hybrids is preferred to prevent seed escape from miscanthus stands. Other aspects that have influence on biomass quality like ripening behaviour (influencing the water and N contents of the biomass) and morphological characteristics with influence on the contents of Cl, K and silica (Si) may be of interest in future breeding programs.

4.2.4. Ecological demands

Miscanthus can be grown on a wide range of soils. The most important soil characteristic is the water holding capacity. Sites with stagnant water are unsuitable. The highest yields are produced on soils with a good water holding capacity. Establishment after planting is better on sandy soils, mainly due to lower competition by weeds, while in the long run yields are higher on heavy soils with improved water availability [59].

Temperature. M. × *giganteus* begins growth from the dormant winter rhizome when soil temperatures reach 10–12°C [60]. Leaf expansion occurs between 5°C–10°C, depending on the genotypes [61]. The main problem of miscanthus production in northern Europe is the poor over-wintering of the rhizomes of the productive genotype *Miscanthus* × *giganteus* in the first winter after planting [19]. Freezing tests showed that *M.* × *giganteus* rhizomes removed from the field in January are killed at temperatures below −3.5°C while the rhizomes of *M. sinensis* survived until −6.5°C [62]. Field trials to screen the winter hardiness of different miscanthus genotypes showed that *M. sinensis* and its hybrids can withstand soil temperatures of −5.4°C while *M.* × *giganteus* rhizomes die off at −3.4°C [63].

Vegetation and photoperiod. M. sinensis forms new shoots during the entire vegetation period while *M. sacchariflorus* forms 80% of its shoots in spring, so the former has a longer flowering period. Initiation of flowering is dependent upon the location where the genotype comes from. The further south in Japan the genotype originated, the later heading starts [50]. Artificial induction of flowering can be attained by dark treatment similar to the dark period of the natural stands where the genotype originates [51].

4.2.5. Biomass yields

Most yields reported for miscanthus in Europe have been assessed using the ‘standard’ genotype *Miscanthus* × *giganteus*. Miscanthus stands need 3–5 years to become fully established and reach the maximum yield level [64,65].

Yields above 30 t DM ha^{-1} are reported for locations in southern Europe with high annual incident global radiation and high average temperatures (e.g. 6200 MJ/m^2 and 15.4°C; data for southern Portugal) but only with irrigation. In central and northern Europe (from Austria to Denmark) where global radiation and average temperatures are lower (e.g. 3500–3900 MJ m^{-2} and 7.3–8.0°C; data from Denmark and Germany), yields without irrigation are more typically 10–25 t DM ha^{-1} [7]. In central Europe miscanthus is harvested in early spring because the stems dry during winter and part of the ash, Cl and K contents are leached by precipitation, which substantially improves combustion quality. A delayed harvest is preferred because of the improved biomass quality, but it also results in yield losses of about 25% [66].

Field trials with different miscanthus genotypes by Hotz, Jørgensen and Clifton-Brown [63,65,67] showed that the differences in yield and quality between the genotypes can be explained by their distinctive physiological development. Late flowering and late senescing genotypes have a more extended growing season and therefore can form higher yields. On the other hand their biomass contains higher concentrations of minerals at harvest, especially N, because the relocation of nutrients from the above ground shoots to the rhizomes starts later. *M. sinensis* genotypes are characterized by thinner stems which have a taller surface where leaching of Cl and K can occur, but in the same time they have are more leavy.

At most European locations the yield potential of *M. sinensis* genotypes is inferior compared to *M.* × *giganteus* [67]. In more northern, cooler regions, such as Denmark, *M. sinensis* genotypes from Japan can reach similar yields as *M.* × *giganteus* [68]. In southern and central Europe *M.* × *giganteus* is still a very productive genotype, however, new hybrids were produced that can reach or even outyield *M.* × *giganteus* at central to southern European locations [69].

4.2.6. Biomass characteristics

The fuel characteristics reported for miscanthus biomass are listed in Table 4. The main problem of miscanthus biomass with regard to combustion is its relatively low ash melting point. However, while there are reports of sintering tendencies at temperatures as low as 600°C [70] other authors report that miscanthus can have a higher ash softening temperature than straw [70]. Genotypes vary significantly in their biomass quality. At a southern German location the water, ash, N and Cl contents of the biomass of *M. sinensis* genotypes at spring harvest were on average 29%, 23%, 26% and 75%, respectively, lower than that of *M.* × *giganteus*, but DM yields were 52% lower, too (Lewandowski, unpublished results).

Biomass characteristics of miscanthus are mainly a function of location. For example, biomass ash contents are correlated with high silt and clay content of the soil [71]. The most important management tool to improve biomass quality in miscanthus is a delayed harvest. Following senescence in autumn and shoot death after frost, Cl, K and ash components are leached from the shoots by precipitation [72]. Leaf losses over winter alter the quality of the harvested biomass, too, as leaves contain higher amounts of minerals like N and K [54].

4.2.7. Management of miscanthus as a bioenergy crop

Establishment. The sterile hybrid *M.* × *giganteus* has to be propagated vegetatively via rhizomes (macro-propagation) or by tissue culture (micro-propagation). Methods for macro-propagation, i.e. mechanical cutting of rhizomes in the field, are under development [73]. While the costs for micro-propagated plant material are about 3000 to 6000 Euro (US$ 2979–5958) [1] per hectare, it is estimated that macro-propagation costs can decrease to around 350 Euro per hectare (US$ 348) [7]. Seeds were produced by inter- and intraspecific crosses of *M. sinensis* and *M. sacchariflorus* genotypes. Miscanthus seeds are very small (1000 seeds weigh about 250–1000 mg), have low nutrient reserves, and require high temperature and moisture for germination. Seed establishment methods still have to be developed, for example by development of coating material.

Ploughing is recommended before planting miscanthus. To avoid frost damage planting should be done when the frost period (< -3°C) is finished. The optimal planting density is 1 to 2 plants m^{-2} [19,59,74]. In general, irrigation during the first growing season improves establishment rates.

The main risk factor for the production of *M.* × *giganteus* in northern Europe is poor over-wintering in the first year. In areas where soil temperatures fall lower than −3.5°C more frost-tolerant genotypes like *M. sinensis* or its hybrids are recommended [63].

Fertilizer and input demand. Since miscanthus did not respond to N fertilization on several sites in Europe it was concluded that N fertilization is necessary mainly on soils with low N contents. At locations with sufficient N mineralisation from soil organic matter N fertilization can be avoided or limited to 50–70 kg ha^{-1} yr^{-1}.

The overall nutrient requirements for N, phosphorus (P) and calcium (Ca) are about 2–5, 0.3–1.1 and 0.8–1.0 kg per t of dry matter [69] and for K 0.8–1.2 kg [75].

Weed and diseases. Weed control in the year of planting is an important measure to ensure establishment of the poorly competing miscanthus plants. Various herbicides suitable for use in maize or other cereals can be used [76].

To date, there are no reports of plant diseases significantly limiting the productivity of miscanthus.

Harvest frequency and time. Miscanthus can be harvested only once a year since multiple cutting would over-exploit the rhizomes and kill the stands. The harvest window depends on the local conditions and is between November and March/April. The later the harvest can be performed, the more the combustion quality improves since the moisture content and the mineral contents decrease; however, there is

[1] Conversion of EURO to US$ is calculated on the basis of currency values for the beginning of the year in which the publication appeared.

a trade-off, since the biomass yield decrease as well. For economic reasons a late harvest at a water content lower than 30% is recommended because the costs for harvesting and drying of the biomass are increasing with the water content [77,78].

4.3. Reed canary grass

4.3.1. Origin

Reed canarygrass belongs to the subfamily *Pooideae* of the *Gramineae* family. It is native to the temperate regions of Europe, Asia and North America. In Europe it can be found throughout the Nordic countries, even in the mountain areas in the north. It is normally found in wet areas like lake shores and along rivers. Reed canarygrass is used as a forage crop mainly in North America, but also to some extent in Eastern Europe, Scandinavia and Japan. In Middle Europe it was used as fodder for horses until the 19th century, but nowadays the interest in using reed canary grass concentrates on material and energy uses.

4.3.2. Physiology

Reed canarygrass is a tall, coarse and erect C_3 grass that reaches a canopy height of 150–300 cm. It has vigorous rhizomes that form 1 cm thick and short branches and a root system that reaches to more than 3 m. When unrestricted, it forms dense masses of broad, leafy foliage. The panicles are compact, erect or sometimes slightly spreading and range from 7–40 cm long with branches 1.2–3.8 cm long. Single flowers occur in dense clusters. Inflorescences are green or slightly purple at first, then become tan. Seeds are shiny brown. Seed production of the species is slightly unreliable because of seed shattering and occasionally poor panicle production. Seed often shatters from the upper branches while seed at the base is still immature [79]. The seeds are small, 1000 seeds have a weight of 1 g. The presence of various types and concentrations of poisonous alkaloids has restricted the use of reed canarygrass as a forage crop [80]. The estimated life time of a plantation is 10 years [81].

4.3.3. Genetic background and availability of varieties

Reed canarygrass is a highly self-sterile allo-tetraploid plant ($2n = 4x = 28$) [82]. There is a large variation in morphological characters between as well as within different ecotypes, which can be utilized in plant breeding activities [83].

As reed canarygrass is used as a forage crop there are breeding programs going on at several locations, aiming to improve the nutritional quality as well as yielding capacity. Several commercial varieties for forage purposes are available on the market, mainly in United States, Canada and Eastern Europe. The recent novel application of this grass for material and energy uses means that new types of cultivars have to be developed. Compared to forage varieties, the contents of N and K should be lower, the lignin content higher, and the plant morphology should be characterized by a higher share of thicker stalks. New breeding programs aiming to develop varieties for biofuel production were initiated about 10 years ago in Sweden and Finland, and the first variety from these programs has been released but is still under seed multiplication [84].

4.3.4. Ecological demands

Reed canarygrass is a persistent species, which grows well on most kinds of soils [85]. It is one of the best grass species for poorly drained soils and tolerates flooding better then other cool-season grasses. Even though it naturally grows in wet places, it is nevertheless more drought resistant than many other grass species [86]. On wet soils, the fortification of the top soil by the vigorous rhizomes and roots is a particular advantage. The highest yield can be obtained on organic soils.

Temperature. Reed canarygrass is adapted to and grows very well in a cool temperate climate. It has also good winter hardiness and survives very well in northern Scandinavia.

Photoperiod. Reed canarygrass has a dual photoperiodic induction requirement for flowering: exposure to short days for primary induction followed by long days for initiation of floral primordial and inflorescence development (secondary induction). The critical photoperiod for secondary induction strongly depends on the origin of the genotype [87]. When a number of populations from northern Sweden (64–66°N) were transferred to southernmost part of the country (56°N), some of them did not produce any panicles at all.

4.3.5. Biomass yields

Reed canarygrass has been evaluated as a bioenergy crop at a number of sites in Sweden for more than 10 years. In field trials at 10 locations the variety Palaton was planted with the objective to study the sustainability and yielding capacity during 10 years of ley. The result shows that there are considerable differences in yield between different soils. Yields were much higher on soils with less than 15% of clay than on clay soils. The highest yields were obtained on humus-rich soils; on average over 8 harvest years, 9 t DM per ha when harvested in autumn, and 7.5 t DM at spring harvest [88].

Finnish experience showed an increase of yields with increased N fertilization with the biggest differences between 0 and 50 kg N and the lowest between 100 and 150 kg N ha^{-1} yr^{-1}. In the third year of the stand a rate of 150 kg N ha^{-1} turned out to be unnecessarily high since no yield effects were measured. The sowing time significantly effected yields of reed canarygrass over three years. Higher yields were measured with sowing in May to June instead of September. No significant yield increases or decreases were recorded from the second year on when the ley aged over 7 years, yields were, however, significantly lower in years with low precipitation [23].

4.3.6. Biomass characteristics

The biomass characteristics reported for reed canarygrass are listed in Table 4. Problems with melted ash or cinder and corrosion has often been the case when using stalky biomass for combustion. In the delayed harvest system these problems are almost eliminated. During the winter there is a decrease in content of elements such as K, Ca, magnesium (Mg), P and Cl. This change in chemical composition is caused by leaching and leaf losses during the winter, which significantly modify the chemical and physical properties of the ash. Most relevant is that the initial ash deformations temperature is raised [89]. The silica content, however, increases over winter, probably due to contamination with soil.

The content of ash and of major elements in the ash show considerable differences between different locations. The soil type has a great influence; high ash contents are measured in reed canarygrass biomass grown on heavy clay soils and low contents in biomass grown on humus-rich and organic soils [90].

4.3.7. Management of reed canary grass as a bioenergy crop

Establishment. Reed canarygrass is established by seeding. Best stands are obtained when sown not deeper than 1–2 cm in a well-prepared, firm seedbed. Seeds are normally drilled in rows, at least under Swedish conditions 12.5 cm row spacing is commonly used. Rolling after seeding will help to keep the moisture in the seedbed. Recommended seeding rate is 15–20 kg ha^{-1}.

Fertilizer and input demand. When reed canarygrass is grown as a bioenergy crop the recommended levels of fertilizer differ from those for fodder production. Experiences from Swedish field trials over almost 10 years resulted in the following recommendations. In the year of sowing an amount of 40 kg N, 15 kg P and 50 kg K ha^{-1} is optimal for a good establishment of the crop. The year after sowing the most economic result is reached when applying 100, 15 and 80 kg ha^{-1} of N, P and K, respectively. During the following years the fertilization rates can be decreased when the delayed harvest system is applied because of the translocation of nutrients at the end of the growing season and leaching during the winter. The removal of nutrients is smaller than in a summer or autumn harvest system. Recommended rates are 50, 5, and 20 kg ha^{-1} of N, P and K, respectively, in every spring.

Weed and diseases. Seeds of reed canarygrass are generally rather slow to germinate and they show various degree of dormancy. Weed competition can therefore be a problem in the first year. Broadleaf species can be controlled with common herbicides. From the second year on, weeds are no problem, since an established reed canarygrass stand is very competitive.

Leaf spot diseases have occasionally been observed on reed canarygrass but there are no reports whether those leaf spots cause any economic losses. A new gall midge has been discovered in northern Sweden, which feeds on reed canarygrass [91]. The area of distribution of the gall midge and its potential as a pest are unknown, and methods of controlling it are not available either.

Harvest frequency and time. Poor fuel quality and the need of expensive artificial drying exclude the summer and autumn harvest alternatives for reed canarygrass in Sweden and other regions with similar climatic conditions. The delayed harvest concept, when the crop is left on field during the winter and harvested as senescent material the following spring, has been developed in Sweden. The harvest is performed when the soil is dry enough for carrying the harvesting machinery and the crop is dry enough for storage without artificial drying ($>$ 80% DM) [92]. In Sweden delayed harvest is normally performed in April to May. With this system the grass can grow undisturbed during the whole of the previous season and build up a store of carbohydrates in the underground parts. A sufficient reserve of carbohydrates is important for the plants to survive a long winter and for an early start of growth in spring.

4.4. *Arundo donax*

4.4.1. *Origin*

Arundo donax belongs to the subfamily *Arundinoideae* of the Gramineae family [93,94]. *Arundo donax* is the only wide-ranging species within the *Arundo* genus [94]. *Arundo donax* is thought to have originated from Asia [95,96] but is also considered as a native species in the countries surrounding the Mediterranean Sea. From this area, it has become widely dispersed by man into all of the subtropical and warm-temperate areas of the world because of it's multiple uses e.g. for musical instruments, rayon, paper and pulp, particle boards, hand-woven baskets, fishing roars, fencing, shading or as ornamental [93]. Therefore, it is currently found growing in India, Burma, China, USA, Australia, Southern Africa, regions adjoining the Nile River and in the Mediterranean region [97]. The rapid spread of this species is probably attributed to its high productivity [96].

Because of its widespread distribution and multiple uses, it has been given several common names. The most widely employed names are merely translation of the simple epithets 'cane' or 'common cane', while the scientific community has adopted the common name 'giant reed'.

4.4.2. *Physiology*

Arundo donax is a tall, perennial C_3 grass and it is one of the largest of the herbaceous grasses.

It grows in dense clumps; the stems can reach a height up to 8–9 m, exhibiting growth rates of 0.3–0.7 m per week over a period of several months during the vegetative stage when conditions are favourable [93]. Stems arise during the whole growing period from the large knotty rhizomes. They do not all emerge at the same time, and later emerging shoots fail to grow well and often die off, probably due to shading.

The fleshy, almost bulbous, creeping rootstocks (rhizomes) form compact masses from which arise tough fibrous roots that penetrate deeply into soil. The rhizomes usually lie close to the soil surface (5–15 cm deep, maximum 50 cm), while the roots are more than 100 cm long [98].

The culms reach a diameter of 1–4 cm and are commonly branched in plantations that are 2 years old or more. They are upright, stout, glabrous, hollow, with walls 2–7 mm thick and divided by partitions at the nodes. The nodes vary in length reaching up to 30 cm. The outer tissue of the stem is of a siliceous nature, very hard and brittle with a smooth glossy surface that turns plain golden yellow when the culm is fully mature [93,94,99].

In each node, an elongated, heart-based, smooth, cauline, membranaceous 30–70 cm long and 5–8 cm broad leaf is attached with flat blades and tufts of hair at the base [93,94,99].

Inflorescences appear between August to November but not all shoots flower in the same year. The terminal inflorescences are single, 30–60 cm long with scabrous branches, feathery with silky hairs. The spikelets are 8–16 cm long and lanceolate. Each spikelet contains 2–7 flowers. The florets are all bisexual except the reduced uppermost one [93,94,99].

It is reported that *Arundo donax* is an asexual reproductive species, due to seed sterility, caused by the failure of the megaspore mother cell to divide [100]. In experiments conducted in India, although viable seeds were produced in large numbers no seedlings were observed in the field due to the effect of allelopathy that prevents germination [98].

4.4.3. *Genetic background and availability of varieties*

Due to the asexual reproduction of *Arundo donax*, its genetic variability and the chances for finding new genotypes or varieties are low. This was shown by band scoring and analysis, conducted under 'The European Giant reed (*Arundo donax* L.) Network' for a large number of natural wild populations grown in Greece, Italy and southern France, using the Random Amplified Polymorphic DNA (RAPD) method. The analysis revealed that the polymorphic bands represent a small percentage of the total number of bands produced by the primers. This observation indicates the low genetic polymorphism among the studied populations and a rather uniform genetic pool. However, according to the results from the electrophoresis tests on these populations, there was a clustering of the selected populations in relation to their geographical origin, reflecting restricted migration of germplasm.

The base chromosome number for the *Arundo* genus is 12. The *Arundo* genus contains three species that are native to the "Old World". *Arundo donax* L. ($2n = 110$) is the only wide-ranging species that occurs from Spain to India. The other species are *Arundo plinii* Tura ($2n = 72$) of the Mediterranean region, and *Arundo formosana* Hackel, which is endemic to Taiwan [93,94]. Seed setting is reported to be poor in India because of failure of meiosis in a majority of ovules [100]. No seeds at all are produced in European locations. Despite the comparative uniformity of *Arundo donax*, there are some reports on the existence of varieties of this species. The best known is the variety *Arundo donax* var. *variegate* (var. *versicolor*, var. *picta*) ($2n = 40$), which is a diminutive of the typical *A. donax* [93,101]. This variety grows denser and produces a higher number of culms and more leaves per rhizome than the typical *A. donax,* and the outer tissue of the stem is of siliceous nature, very hard and brittle. Duke [99] reports on another variety called *Arundo donax* var. *macrophylla* ($2n = 40$), that has large and glaucous leaves. According to Perdue [93] other varieties were selected that do not differ significantly from typical *Arundo donax* except for their variegated leaves.

4.4.4. Ecological demands

Giant reed tolerates a wide variety of ecological conditions. It prefers well-drained soils with abundant soil moisture. It can grow in all types of soils from heavy clays to loose sands and gravelly soils [93] and tolerates soils of low quality such as saline ones, too.

Giant reed is classified as a Mesophyte or almost a Hydrophyte or Xerophyte. These classifications were given because it can survive just as well under very wet as under dry conditions for long periods. It is commonly referred as a drought resistant species because of its ability to tolerate extended periods of severe drought accompanied by low atmospheric humidity. This ability is attributed to the development of coarse drought-resistant rhizomes and deeply penetrating roots that reach deep-seated sources of water.

Temperature. *Arundo donax* is a warm-temperate or subtropical species, but it is able to survive frost. When frosts occur after the initiation of spring growth it is subject to serious damage [93].

4.4.5. Biomass yields

The potential productivity of giant reed can reach up to 100 t fresh matter ha^{-1} yr^{-1} in the second or third growing period under optimal conditions in a warm climate with sufficient irrigation [102]. Yields reported in Spain showed 45.9 t DM ha^{-1} on average, ranging from 29.6 to 63.1 t [103]. In Greece, the recorded average DM yields, estimated from 40 giant reed populations, for the first, second third and fourth growing periods were 15, 20, 30 and 39 t ha^{-1}, respectively, on irrigated plots. Stems constituted the largest part of the harvested material and amounted, on average, for 67%, 87%, 83% and 86% of the DM, for the first, second, third and fourth growing periods, respectively. The results show increasing yields from the first to the third year. From the third year onwards, stable, increasing and decreasing yields have been measured, so no clear conclusion can be drawn on when the maximum yields of giant reed are achieved.

Because high yields have been obtained from unimproved wild populations and by using conventional cultivation methods, future breeding efforts and optimized production methods will probably lead to an increase in biomass yields from giant reed.

4.4.6. Biomass characteristics

The calorific value of different aerial parts of a number of *Arundo donax* populations grown in Greece, ranged from 17.3 to 18.8 MJ (stem) and 14.8 to 18.2 MJ kg^{-1} DM (leaves) depending on the population and the growing periods. Leaf samples of plants grown without irrigation had statistically higher calorific value (17.2 MJ kg^{-1} DM) in comparison to the irrigated treatments (16.1 MJ kg^{-1} DM). Due to lower ash content of the biomass, irrigation slightly increased the contents of volatiles in stems, too; ranging from 75% to 77% of DM (unpublished results).

Depending upon the population and the growing period, the contents of ash and fixed carbon contents ranged from 4.8% to 7.4% and 17.7% to 19.4% of DM, respectively. Apart from the physical attributes of stems the high measured values for ash should be attributed to the contribution of sheath as well as sample contamination by soil, which raises the ash content (unpublished results).

At the February harvest the N content in stems ranged from 0.2% to 0.4% and reached 1% of DM in the leaves (unpublished results).

Compared to the plants that received 60 kg N ha^{-1}, the highly fertilized plants (120 kg N ha^{-1}) had a significantly higher nitrogen content in stems 94 days after fertilization and in leaves 30 and 60 days after fertilization. The higher nitrogen content in stems and leaves of the highly fertilized plants remained until the end of the growing season, though it was not statistically significant (unpublished results).

4.4.7. Management of giant reed as a bioenergy crop

Establishment. The establishment period is the most critical point of giant reed cultivation and has major influences on productivity and economical viability. The two main factors determining establishment success and costs are the propagation material and the planting density.

Due to seed sterility giant reed has to be propagated vegetatively. Preliminary tests on the ability of this grass to be micropropagated showed satisfactory results, though micropropagated plantlets have not yet been planted in the field. Planting of rhizomes, whole stems and stem cuttings have been tested, but appropriate machinery for this operations is not yet available [104,105]. In the tests done so far, rhizome establishment has turned out to be the most promising. The planting of large rhizome pieces with well-developed buds directly into the field early in spring in southern European areas succeeded in attaining establishment rates of nearly 100% [106]. The main drawback of propagation via rhizomes are the higher costs compared with stem cuttings and whole stem planting because of the lack of mechanization. Furthermore stem cuttings and whole stems are easier to handle. Although the sprouting capacity of whole stems was good, they failed to form dense stands, resulting in low biomass yields. However, these trials showed that adapting harvest time, selecting the appropriate shoot size and portion (along the whole shoot) and handling of the shoots might improve their sprouting capacity and the results of establishing stem cuttings or whole shoots [106]. Further investigations are strongly recommended.

For a comparison of the two plant densities of 25,000 plants ha^{-1} (50 cm × 80 cm) and 12,500 plants ha^{-1} (100 cm × 80 cm), it turned out that the lower planting density resulted in taller and thicker stems due to less competition for nutrients and light. The lower planting density was also more productive than the higher one in the first two growing periods and can therefore be recommended as more economically viable [106].

Irrigation. Giant reed has been reported to grow without irrigation under semi-arid southern EU conditions [107]. During the productivity trials of the 'Giant Reed Network' several irrigation rates have been applied. The irrigation rates were I_0 = rain fed, $I_1 = 1/2I_2$ and I_2 = 100% of the maximum water requirements of the plants (potential evapotranspiration—ETo). The irrigation applied for I_0 ranged from 44 to 108 mm (applied only for fertilization purposes), I_1 ranged from 459 to 800 mm and I_2 ranged from 869 to 1404 mm, depending on the year.

In general, irrigation had a considerable effect on growth and biomass production since the plant used effectively any possible amount of water. The irrigated plants formed denser stands and higher yields [108]. Total dry matter yield in the I_0 treatment was constant at about 19 t ha^{-1} over three growing periods, which may indicate that these are the maximum yields to be anticipated under water-limited conditions. It was also observed that the highly irrigated giant reed plants reached their peak of productivity after the second growing period.

The lack of statistically significant differences between the moderate and the high irrigation rates may lead to the conclusion that it is more economical and environmentally favorable to grow giant reed under moderate irrigation.

Fertilizer and input demand. Before establishing the plantation a sufficient amount of K and P should be applied if the nutrient status of the soil is poor. In the "Giant Reed Network" project the yield effect of two nitrogen fertilization levels (40 and 120 kg N ha^{-1}) was tested. The highly fertilized plots only yielded approximately 1 t DM ha^{-1} more, an increase which was not significant [108].

This led to the conclusion that moderate nitrogen fertilization of giant reed is favorable for both economic and environmental reasons.

Weed and diseases. Due to its large leaf mass and high growth rates giant reed does not face significant weed competition from the second year on. For safe establishment, however, herbicide application is recommended for the first year.

Giant reed is a highly pest resistant crop, and so far only two pests have been reported. Giant reed is an alternative host plant for *Zyginidia quyumi* in Pakistan [109]. During early growth stages new shoots are in a succulent condition and may be attacked by *Sesamia* spp. and die. However, new sprouts emerging from the rhizome buds soon replaced the attacked ones.

Harvest frequency and time. Giant reed can be harvested each year or every second year, depending on its use. Two harvests per growing period are feasible, but repeated clipping did not sustain high growth rates and total production declined [98].

In southern EU regions late winter harvest is recommended to attain a reduction in the moisture content of the stems.

5. Discussion

The characteristics and the ecological/climatic demands of the four most investigated and widely cultivated perennial rhizomatous grasses (PRG) in the US and Europe are described above. Should research and future production of biomass for energy concentrate on one of these grasses or continue to investigate the potentials of them all? In the following sections the pros and cons of different grasses and the needs for producing various PRGs are discussed under different headings.

5.1. *Ecological/climatic conditions*

The main reason for developing different PRG as bioenergy crops is the need to establish appropriate PRG types for different ecological/climatic zones. Initial experiments to compare miscanthus (*Miscanthus* × *giganteus*) and switchgrass ('Kanlow') under southern German conditions showed that miscanthus outyielded switchgrass at a location with heavy soil and better water supply, while switchgrass outyielded miscanthus on a sandy soil with occasional drought [110].

The main climatic limitations to be overcome in Europe are the low winter temperatures in northern Europe and the drought periods in the southern European summer. The farther north perennial grasses are planted, the more likely cool season grasses are to yield more than warm season grasses [15]. Low winter temperatures and short vegetation periods are major limitations on the growth of C_4 grasses in northern Europe, making reed canarygrass the only choice for countries like Finland and central to northern Sweden. With increasing temperatures towards central and southern Europe the productivity of C_4 grasses and therefore their biomass yields and competitiveness increase. The potential zone for miscanthus production in Europe has been extended northwards by the screening and breeding of more frost-tolerant genotypes [111]. From central to southern Europe temperatures as well as water scarcity increase. The adaption of miscanthus to drought zones has not yet been a subject of research. It is expected that miscanthus stands under severe drought will die off. Because switchgrass seems to be more drought tolerant than miscanthus it can probably be produced in those areas that are too dry for miscanthus production. The same is true for giant reed that can survive severe water stress and still produce considerable yields under drought conditions [107,108].

PRGs are new energy crops and some, like miscanthus and giant reed, still retain wild-type characteristics such as high seed dormancy levels and insufficient winter rest ability. Breeding work for the development of bioenergy varieties is still only just beginning for all PRG, and has the potential to develop varieties more specifically adapted to the different ecological/climatic zones. But it has to be emphasized that breeding of PRG is a time consuming process and the performance of new varieties in the field can only be assessed in the second or third year after establishment [69]. It is therefore expected that different PRGs will be needed to provide appropriate grass types for bioenergy production in the different ecological/climatic regions of Europe.

5.2. Risk management

As has been discussed above, successful biomass production from PRG requires the choice of the suitable grass genus and variety for the given local conditions. A mixture of different grasses within the same region may, however, lead to reduction of risks. This is mainly true for the reduction of the risk of epidemic pest and disease outbreak. Another reason for growing different grasses together can be the optimization of biomass supply for a heating or power plant, since different grasses mature and can be harvested at different times. Reed canarygrass dies off earlier and resprouts earlier in spring than miscanthus and may therefore be harvested earlier. This could extend the period of bioenergy provision to the combustion plant and reduce the need for storage. Whether adaption of the combustion operation to the qualities of different grass biomasses become necessary will depend on the combustion technique.

A main risk of energy supply by PRG, the stability of yields over successive years, can not yet be estimated since long term productivity trials are lacking. PRG research is still relatively young and most trials are terminated when project financing ends. However, initial results show stability in yields of reed canary grass and miscanthus for up to 10 years [23,112] and, in six year trials with switchgrass, from the 4th to 6th year [113].

5.3. Costs

The costs for a ton of biomass from PRG is a function of (a) area-related costs for the establishment, management and harvest of the crop and of (b) the biomass yield [114]. A cost comparison between the biomass from different PRG therefore depends strongly on specific local yields. This has been shown by a cost analysis done by Hallam [115] for switchgrass and reed canarygrass biomass grown at the same locations. The break-even prices (obtained by dividing the costs per hectare by the expected yield per hectare) ranged from Euro 51.04 to 87.01 t^{-1} (US$ 48.06 to 81.93 t^{-1}) [2] for reed canarygrass and Euro 41.31 to 59.72 t^{-1} (US$ 38.90 to 56.23 t^{-1}) for switchgrass, suggesting lower costs for switchgrass production. The cost ranges within the crops is partly caused by different machine use, but is mostly derived from the harvested yield. Since reed canarygrass only attained average yields of 8.2 and 10.9 t DM ha^{-1}, compared to 11.1 and 11.6 t for switchgrass these lower yields led to significantly higher production costs for reed canarygrass [115].

According to an assessment by Deimling [114], the fuel supply costs (including establishment, crop management, harvest and storage) for miscanthus are 101 Euro t^{-1} DM at a yield level of 10 t and 75 Euro t^{-1} DM at a yield level of 17 t DM ha^{-1}.

Establishment costs represent a large proportion of the production costs of biomass for those grasses that require planting. Table 5 gives an overview of the establishment options and the estimated costs for different PRG.

The establishment costs for reed canarygrass and switchgrass, which are both established by seeding, ranged from 108 to 297 Euro ha^{-1} and 176 to 370 Euro ha^{-1} (102 to 263 and 166 to 348 US$ ha^{-1}) [115]. Conventional establishment of miscanthus (planting of micropropagated plantlets) are about 7772 Euro ha^{-1}, or 518 Euro $ha^{-1}yr^{-1}$ (when allocated over 15 years of production) [114]. Similar high costs are expected for the planting of giant reed. Sure and cheap establishment methods may therefore be a major factor for the economic competitiveness of different PRG.

It is expected that the development of rhizome planting machines will decrease the costs of establishment of Miscanthus and giant reed to 350 Euro per hectare (US$ 348) [7]. Initial trials in Denmark showed that the mechanical harvesting and immediate planting of rhizomes of miscanthus can be successful with the appropriate machinery [116], although further research and technical development is needed. However, rhizome propagation carries the risk of disease spreading. Development of seeds is therefore the preferred and cheapest option for these grasses in future. One problem that could be expected is

[2] Conversion of EURO to US$ is calculated on the basis of currency values for the beginning of the year in which the publication appeared.

Table 5
Ways to establish perennial rhizomatous grasses (unpublished data)

	Seed Establishment		Rhizome establishment		Micropropagation Cuttings	Stem
	In the field	Pre-culture in greenhouse	In the field	Pre-culture in greenhouse		
Reed Canary Grass	X (A)					
Switchgrass	X (A)	X				
Miscanthus			D	X	X (A)	
Giant Reed			D	X (A)		X
Estimated Costs Euro ha^{-1}	120–400	1500–3000	350	3000–6000	3000–8000	2200

X = method safe; D = method in developmental stage; (A) = actually performed method for this grass.

genetic inhomogenity of the seeds (Martin Deuter, pers. comm., Tinplant GmbH). Future research will have to analyze the prospects for seed establishment of miscanthus and giant reed.

5.4. Acceptance

There are concerns about growing non-native species in the US, and so switchgrass is favoured as a bioenergy crop because it is indigenous. Reed canary grass and giant reed are native to Europe, and miscanthus and switchgrass are acceptable there as bioenergy crops as long as precautions are taken that these grasses do not spread as weeds. To prevent spreading of miscanthus the aim of miscanthus breeding is to produce triploid hybrids, like *Miscanthus × giganteus*, that do not form fertile seeds [117].

A mixture of different grasses may improve the public acceptance of bioenergy production because it contributes to landscape visual diversity and can contribute to increased biodiversity by providing habitat to different animals (see [8]). On the other hand, tall grasses like miscanthus may also raise concerns about 'closed' views in the landscape.

An important consideration in the early phases of commercialization of biomass energy is the ease with which the new crops and cropping techniques can be introduced to landowners. An important quality of switchgrass in terms of its perception in America is its strong potential appeal to landowners, for whom cultivation of a perennial crop that can be grown, harvested, and stored like hay with conventional equipment represents an easy interface with current agricultural practices [118]. The same advantages are reported for reed canary grass already being produced in northern Europe.

5.5. Quality of the biomass

The quality of the biomass of grasses may limit the options for potential applications. For use as solid fuel, the biomass should have low contents of water, ash, N, K, Cl and S, the ash melting temperature should be high and the biomass should have a high energy density [72,119]. It should also be possible to collect the biomass of PRG for solid-fuel bioenergy production in one harvest per year. This allows a delayed harvest, leading to reduced production costs due to the single harvest and low water content.

Generally it can be concluded that PRGs for solid bioenergy production should be characterized by highly lignified stems to prevent lodging and to allow a late harvest. Delayed harvesting decreases water content, and water-soluble components like K and Cl can be leached out [68,72].

The combustion quality of grass biomass is strongly influenced by site factors (like the clay content of the soil or weather conditions) and can be managed to a certain extent, e.g. by delayed harvest [72,90,120]. There are significant differences in the fuel qualities of biomasses of different grasses, which can only be quantified when the grasses are grown at the same location, as has been done by Christian [113] at Rothamsted, UK. Results here show that the biomass of the C_4 switchgrass has lower concentrations of ash, N, and K than the biomass of C_3 reed canary grass. Generally the biomasses of C_4 grasses are characterized by lower contents of ash and various minerals than C_3 grasses (Table 4).

It should also be noted that giant reed has a high water content at harvest, and that heterogeneity in shoot maturity leads to a lack of homogeneity in its fuel quality.

6. Conclusions

- Because of their high yield potentials, low input demands and multiple ecological benefits Perennial Rhizomatous Grasses (PRG) can significantly contribute to sustainable biomass production in Europe and the US.
- Among the perennial grasses tested in the US and Europe switchgrass (*Panicum virgatum*), miscanthus (*Miscanthus* spp.), giant reed (*Arundo donax*) and reed canarygrass (*Phalaris arundinacea*) showed the best potential for the production of biomass because they are comparatively high yielding and can be collected in one single harvest procedure per year, allowing the implementation of a delayed harvest system which is the most effective means to improve fuel characteristics of the biomass.
- Yields of more than 30 t DM $ha^{-1}yr^{-1}$ have been measured for switchgrass, miscanthus and giant reed and up to 12 t DM $ha^{-1}yr^{-1}$ for reed canarygrass. Reed canary grass is the lowest yielding of the most important biomass grasses, but it is the only PRG that can be produced in regions with short vegetation periods and cold winters such as northern Europe. Switchgrass and miscanthus can be grown from central to southern Europe, giant reed mainly at lower latitudes.
- The C_4 grasses switchgrass and miscanthus are, on those locations which are suitable for their production, the best PRG to produce biomass as solid biofuel because they best combine high biomass yields with good combustion characteristics of the biomass.
- In the US, miscanthus could be grown as a bioenergy crop alongside switchgrass, and may outyield switchgrass at locations with good water supply.
- The main barrier to the growing of PRG for biomass are the high production costs. In the future, these may be reduced by
  - The development of more cost effective and certain establishment methods,
  - Breeding of varieties adapted to the needs of biomass production,
  - Mechanisation of establishment and harvest of PRG,
  - Further development of the crop management systems for PRG.

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