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Review

Bioenergy from permanent grassland – A review: 2. Combustion

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ABSTRACT

The aim of this review is to summarize current knowledge on suitability and sustainability of grassland biomass for combustion. In the first section grassland management for solid biofuel as well as information on harvest, postharvest and firing technology are described. An extensive grassland management system with one late cut and low level of fertilization is favored for grass as a solid biofuel. The grass harvest usually involves drying in the field and clearing with conventional farm machinery. Pelleting or briquetting improves the biofuel quality. Grass combustion is possible as stand-alone biomass-firing or co-firing with other fuels. Firing herbaceous biomass requires various specific adaptations of the different combustion technologies. In the second section economic and environmental aspects are discussed. Costs for biomass supply mainly depend on yields and harvesting technologies, while combustion costs are influenced by the size and technical design of the plant. Market prices for grass and possible subsidies for land use are crucial for profitability. Regarding biogeochemical cycles a specific feature of combustion is the fact that none of the biomass carbon and nitrogen removed at harvest is available for return to the grassland. These exports can be compensated for by fixation from the air given legumes in the vegetation and sufficient biomass production. Greenhouse gas emissions can be considerably reduced by grass combustion. Solid biofuel production has a potential for predominantly positive impacts on biodiversity due to the extensive grassland management.

1. Introduction

The second part of this review on bioenergy from permanent grasslands focuses on the production and use of solid biofuel, i.e. combustion of grassland biomass for the generation of heat and power. The aim of the review is to summarize current knowledge on suitability and sustainability of grassland biomass for combustion.

Permanent grassland is defined as land used for five years or more for herbaceous forage crops, either cultivated or growing wild (FAOSTAT, 2008). Thus, the term permanent grassland as used henceforth comprises the three main types of managed grasslands (specified for Europe by Soussana et al. (2007)): sown (in this case perennial energy grasses), intensive permanent grassland and semi-natural grassland (similar to the words rangelands, prairies in other regions of the world).

The interest in the use of grassland biomass for solid biofuels in Europe, North America, and Asia has been increasing for the last two decades (Lewandowski et al., 2003b; Xiong et al., 2008). The focus clearly lies on established perennial energy grasses, such as switchgrass, reed canary grass, miscanthus or giant reed. Comprehensive research has been done in this field. Combustion of perennial energy grasses has been established in practice in several European countries (Obernberger, 1998; Pahkala et al., 2008). Compared to perennial energy grasses, much less research work has been done on permanent grasslands that are not sown. Few investigations deal with solid biofuel supply from semi-natural grasslands (Kasper, 1997; Tonn et al., 2007). Main research topics in the field of solid biofuels from grasslands are biomass yields and fuel quality, environmental impacts and economic aspects.

2. Grassland management for combustion

The aim of supplying biomass for combustion is to achieve high energy yields per unit area (GJ ha^{-1}) and best possible fuel quality. The energy yield comprises the biomass yield (t_{DM} ha^{-1}) and the energy content of the biomass (MJ t_{DM}^{-1}). Fuel quality is determined by the physical and chemical properties and influences the entire process of thermal utilization.

Chemical properties of grass biomass, their impacts and available guide values were summarized by Obernberger et al. (2006): the contents of carbon, hydrogen and oxygen which are the main components of solid biofuels are of special relevance for the gross calorific value. The hydrogen content also determines the net

Abbreviations: DM, dry matter; FM, fresh matter; n.r., not reported.

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calorific value. The fuel nitrogen content is responsible for nitrogen oxide formation and should not exceed 0.6% w/w in dry matter (DM). Sulfur is one of the elements responsible for deposit formation, corrosion, and aerosol and sulfur oxide emissions. Sulfur concentration should be lower than 0.1% w/w in the DM. Chlorine as well is involved in corrosion, deposit and aerosol formation. Furthermore it causes hydrogen chloride and dioxin and furan emissions. Chlorine content should be kept under 0.1% w/w in the DM. The ash content influences the choice of the appropriate combustion technology and deposit formation, fly ash emissions, ash storage and utilization/disposal. Major ash forming elements are aluminium, calcium, iron, potassium, magnesium, sodium, phosphorus, silicon, and titanium. They are of relevance for the ash melting behaviour, deposit formation, and corrosion.

Main physical fuel properties are calorific value, moisture content, particle size, bulk density, ash melting behaviour (Obernberger, 1998). The calorific value first of all depends on moisture content, decreasing linearly with rising moisture content (Jenkins et al., 1998; McKendry, 2002). Furthermore it is negatively correlated to the ash content. With every 1% increase in ash concentration the heating value of the fuel decreases by 0.2 MJ kg_{DM}^{-1} (Jenkins et al., 1996).

Fuel properties of grassland biomass vary in a wide range. The stage of vegetation is the major factor to affect chemical composition as well as some physical characteristics.

A number of systematic investigations with grassland biomass consistently come to the result that biofuel quality improves with delayed harvest (Table 1). The contents of the mostly undesired elements as nitrogen, sulfur, potassium, and chlorine decrease significantly with advancing age of vegetation and may fall below the thresholds by delaying harvest until late winter or early spring. Furthermore ash contents decline and ash melting temperature rises (Burvall, 1997; Tonn et al., 2007). A highly lignified biomass is desirable due to the high content of carbon in lignin and resulting high heating value (Lewandowski and Kicherer, 1997).

Delayed harvest improves biofuel properties for three main reasons: first, because the proportion of stems increases and of leaf biomass decreases with senescence as the crop ages (Christian et al., 2006; Landström et al., 1996; Sanderson and Wolf, 1995a) and higher nutrient concentrations are found in the leaves than in the stems (Burner et al., 2008; Frank et al., 2004; Landström et al., 1996; Monti et al., 2008), the total nutrient concentrations in the whole plants fall. Second, nutrient translocation and storage in the below ground plant parts can proceed or be completed before harvest. And third, elements are leached from standing vegetation by precipitation.

Beyond the numerous field experiments only few attempts have been made to model the seasonal pattern of solid biofuel properties of grass. Selected fuel properties of switchgrass were related to weather data in the early nineties of the last century in the United States (Sanderson and Wolf, 1995b). Switchgrass plots were sampled weekly or every two weeks during four years. The samples were analysed for lignocellulose, crude protein, total ash, and potassium. The weather data used for regression analyses were cumulative degree days, calculated from maximum and minimum daily temperature. Concentrations of all constituents regarded were closely related to cumulative degree days. Lignocellulose concentrations increased linearly until a certain number of cumulative degree days. Thereafter, concentrations remained about the same or continued to increase at a much slower rate. Rapid increase in lignocellulose concentration ended at the time of internode elongation. Crude protein, ash, and potassium concentrations decreased curvilinearly with accumulated degree days (Sanderson and Wolf, 1995b). A linear relation between the day of year at harvest and lignocellulose concentration was found for switchgrass in south central regions of the United States (Cassida et al., 2005).

The type of grassland vegetation seemed to have little influence on biofuel properties in southwest Germany. The chemical composition of samples from three different plant communities varied comparatively little at the same stage of grass maturity (Tonn et al., 2007). Results from 10 locations in Iowa showed that the majority of variation in elemental composition occurred within locations, not among them. Evaluation of species-composition and chemical-composition data over the sites indicated certain species were more associated with specific chemical components (Florine et al., 2006).

While delayed harvest positively affects biofuel quality, on the other hand it leads to remarkable biomass losses. For example, dry matter biomass yield reductions of 66–71% are reported from semi-natural grassland between September and February (Tonn et al., 2007), of 20% from switchgrass between September and winter harvest (Lewandowski et al., 2003a; McLaughlin et al., 2002), and of 34% from miscanthus between December and March (Lewandowski and Heinz, 2003).

Different responses of biomass yields and fuel quality to the level of fertilization have been found (Table 2). In some of the investigations grass yields and nitrogen contents increase with rising nitrogen rates (Landström et al., 1996; Lemus et al., 2008; Mulkey et al., 2008; Scholz and Ellerbrock, 2002), while in other experiments nitrogen rates did not influence yields and nitrogen contents (Christian et al., 2008; Lewandowski and Kicherer, 1997; Mulkey et al., 2008). A compilation on the influence of management practices on yields and fuel quality of miscanthus in Europe similarly shows a varying influence of fertilization (Lewandowski et al., 2000).

Overall, management measures to improve fuel quality such as delaying harvest and reducing level of fertilization often lead to decreasing biomass yields. In this conflict priority is given to fuel quality since various options to adapt combustion technology are expensive and/or technically limited (see Section 3.3). Hence, grassland management for solid biofuel production has to be directed primarily at fuel quality and in second instance at biomass yields. An extensive grassland management system with one late cut and low level of fertilization is favored for grass as a solid biofuel.

3. Technology

3.1. Harvest and storage

Harvest, preservation and storage technology of grass as a solid biofuel resembles that for forage, mainly in form of hay. Physical biofuel properties and to a lesser extent chemical composition can be influenced at certain points of the process chain. Moisture contents of 10–20% are the precondition for storability of the grass and as well advantageous with respect to the heating value. As a rule, field drying of the grass and harvesting as baled hay is preferred. Mowing, turning, windrowing, and baling can be done with conventional farm machinery (Lindh et al., 2008; Lötjönen, 2008). Alternatively loose material can be harvested with choppers (Lindh et al., 2008; Styles and Jones, 2008).

Depending on moisture contents in the standing vegetation the harvest chain may contain a period between mowing and baling, when the cut grass is lying in the field for drying. During this field period leaching of undesirable elements can improve biofuel quality (Table 3). Substantial reductions in ash and undesirable elements by leaching are reported from extensive grassland (Kasper, 1997), from banagrass (Turn et al., 1997), switchgrass (Dayton et al., 1999) and straw (Arvelakis et al., 2001; Jenkins et al., 1996; Kasper, 1997; Sander, 1997). Although element leaching by rainfall can improve fuel quality of grassland biomass, some problems with the targeted application of this strategy by prolonging

Table 1
Seasonal variation of characteristics of grassland biomass relevant for combustion.

Vegetation/grass species, region	Reference	Harvesting period	Heating value	Ash content	C	H	O	N	S	Cl	K	P	Na	Ca	Mg
			[MJ kg_{DM}^{-1}]	[% in DM]									[mg g_{DM}^{-1}]		
Meadow foxtail and reed canary grass communities, Germany	Kasper (1997)	June	17.5–18.0	4.1–5.8	46.0–49.7	5.5–5.9	39.4–41.1	1.00–1.81	0.09–0.17	0.67–0.83	0.6–1.78	0.25–0.32	1.1–2.8	2.9–5.4	1.0–2.7
		August/ September	17.2–18.0	4.6–6.9	45.4–47.4	5.6–6.2	38.4–39.8	0.74–1.59	0.11–0.17	0.51–1.16	0.21–0.9	0.34–0.89	0.43–1.0	2.5–3.1	0.81–1.93
Five semi-natural grassland communities, Germany	Tonn et al. (2007)	August	–	–	–	–	–	1.28–1.89	0.13–0.17	0.25–0.37	1.0–1.5	–	–	–	–
		February	–	–	–	–	–	0.9–1.3	0.09–0.17	0.02–0.1	0.3–0.4	–	–	–	–
Ten locations, mixed vegetation, Iowa	Florine et al. (2006)	Late June	17.7–19.5	5.8–11.8	48.4–53.7	4.8–6.0	29.5–37.5	0.7–2.3	0.07–0.34	0.08–0.76		–	–	–	–
Reed canary grass, Sweden	Landström et al. (1996)	August	–	5.58–5.98	–	–	–	1.18		0.36	1.12	0.17	–	–	1.2
		April–May	–	4.40–4.68	–	–	–	0.93		0.08	0.25	0.11	–	–	0.5
Reed canary grass, Sweden	Burvall (1997)	July–October	17.9	6.4	46	5.7	–	1.33	0.17	0.56	1.23	0.17	0.2	3.5	1.3
		March–May	17.6	5.6	46	5.5	–	0.88	0.09	0.09	0.27	0.11	0.2	2.0	0.5
Reed canary grass, England	Christian et al. (2006)	December/ January	–	–	–	–	–	0.65–0.94	–	–	0.3–0.4	0.5–0.7	–	–	–
		January/ February	–	–	–	–	–	0.59–0.87	–	–	0.1–0.3	0.3–0.5	–	–	–
Switchgrass and reed canary grass, north China	Xiong et al. (2008)	September	17.1–17.9	7.7–12.6	41.3–43.5	6.1–6.7	–	0.35–1.25	–	0.83–1.2	0.3–1.35	0.35–1.25	0.11–0.51	0.2–0.55	–
		April	16.3–17.4	3.48–9.81	43.8–46.9	6.0–6.1	–	0.24–0.74	<0.01	0.21–0.25	0.21–0.27	0.2–0.6	0.09–0.10	2.5–3.2	–
Switchgrass and coastal panic grass, England	Christian et al. (2002)	September–November	–	–	–	–	–	0.6–1.6	–	0.2–0.41	0.26–0.84	0.51–1.49	–	–	–
		November–February		–	–	–	–	0.5–1.1	0.005–0.01	0.07–0.27	0.11–0.44	0.42–1.02	0.04–1.4	3.1–6.2	0.10–0.22
Switchgrass, Iowa	Lemus et al. (2002)	October	–	5.9	48.5	5.1	39.8	0.56	0.09	–	–	–	–	–	–
		January	–	3.8	47.0	5.6	43.0	0.51	0.20	–	–	–	–	–	–
Miscanthus															
Sweden	Lewandowski et al. (2003a)	October	–	3.87	–	–	–	0.50	–	0.44	0.95	–	–	–	–
		February	–	1.94	–	–	–	0.39	–	0.12	0.29	–	–	–	–
Denmark		October	–	3.61	–	–	–	0.64	–	0.51	0.11	–	–	–	–
		February	–	1.66	–	–	–	0.46	–	0.09	0.28	–	–	–	–
England		November	–	4.27	–	–	–	0.38	–	0.46	0.72	–	–	–	–
		January	–	3.05	–	–	–	0.31	–	0.24	0.49	–	–	–	–
Germany		November	–	3.40	–	–	–	0.44	–	0.15	0.95	–	–	–	–
		February	–	2.30	–	–	–	0.36	–	0.07	0.61	–	–	–	–
Portugal		October	–	4.87	–	–	–	0.57	–	0.48	0.80	–	–	–	–
		January	–	3.52	–	–	–	0.36	–	0.19	0.34	–	–	–	–

Table 2
Nitrogen fertilization level, biomass yields and nitrogen contents in grassland biomass.

Grass species	Country, years	N rate [kg ha^{-1}]	Biomass yield [t_{DM} ha^{-1}]	N content [% in DM]	Reference
Reed canary grass	Sweden, 1991–1995	100 200	6–9[a] 6–11[a]	0.6–1.0 1.0–1.4	Landström et al. (1996)
Cocksfoot	Germany, 1994–1999	0 75 150	6.7 7.5 8.5	1.6 1.8 2.3	Scholz and Ellerbrock (2002)
Switchgrass	United States, 1998–2002	0 50 100 200	3.9[b] 4.5[b] 4.9[b] 5.2[b]	0.48 0.45 0.46 0.51	Lemus et al. (2008)
Miscanthus	Germany, 1991–1995			Stems/ leaves	Lewandowski and Kicherer (1997)
		0	8.9	0.12/ 0.58	
		50	8.1	0.19/ 0.76	
		100	13.7	0.09/ 0.30	
		150	10.5	0.18/ 0.64	
Miscanthus	UK, 1993–2006	0 60 120	13.0[c] 12.4[c] 12.9[c]	n.r. n.r. n.r.	Christian et al. (2008)
Mixture of switchgrass, banagrass and big bluestem	US, 2001–2003		Location 1/2	Location 1/2[d]	Mulkey et al. (2008)
		0	2.6/2.6	0.27/ 0.59	
		56	4.9/2.8	0.33/ 0.73	
		112	5.3/2.8	0.43/ 0.65	
		224	5.5/3.0	0.53/ 0.77	

[a] Average of second and third ley year.
[b] Average of five years.
[c] Average of 14 years.
[d] Harvest time at killing frost.

the field period after mowing may occur. The results of investigations indicate that an amount of about 100 mm of rainfall is required for considerable effects on element concentrations. In many regions it might take too much time to achieve 100 mm of rain, leading to unacceptable high dry matter losses in the field and to a high risk of displacing the baling into periods with unfavorable weather conditions.

The well-known problem of high dry matter losses in the process chain of hay making also occurs when harvesting grassland biomass for solid biofuel. These losses comprise plant respiratory losses, leaching losses, and mechanical losses during machinery operations, reaching a total of 10–30% of dry matter (McGechan, 1989a). Harvesting senescent grasses at very late cutting dates may in addition lead to high biomass losses due to extreme lodging. Total harvest losses of reed canary grass are reported to be 20–40% at the best, and 50–60% at the highest (Lindh et al., 2008).

When clearing the field achieving high energy densities (GJ m_{DM}^{-3}) is a key factor for reducing expenditures for transport and storage (Kasper, 1997). Energy density as the product of lower heating value and bulk density can mainly be influenced by dry matter contents and bulk densities. The type of balers used determines bulk density (Table 4). Large round and square balers are common in practice to harvest herbaceous biomass for solid biofuel. Trucks, platform trailers, and bale collecting trailers can be used for transport.

Hay storage losses are known to be low from forage conservation, accounting for 1–3% of dry matter at moisture contents below 20% (McGechan, 1989b). Dry matter losses in switchgrass bales ranged from 4% to 13% during outside storage and from 0% to 2% during inside storage (Sanderson et al., 1997). Storage experiments indicate that biofuel quality may remain constant or deteriorate during both inside and outside storage under certain circumstances (Wiselogel et al., 1996). However, the factors leading to the different results cannot be identified yet.

Key points for improving efficiency of harvest, transport, and storage are to manage the weather risk to achieve the required low-moisture contents, to reduce biomass losses, to achieve highly compacted and stable bales and to establish efficient bale logistics.

3.2. Processing

3.2.1. Comminution

Depending on the design of the combustion plant the grass biomass can be fed in different shapes and sizes. Except from firing systems for whole bales a certain degree of comminution is required, ranging from bale slicing via chopping, cutting, and shredding to milling. While chopping can be integrated at harvest with both balers and choppers, the other operations for comminution have to be carried out with stationary equipment, usually at the combustion plant. Size reduction as well is necessary before pelleting or briquetting. Common machines are hammer-, knife-, and disk-mills, and various choppers, chippers, and shredders (Yu et al., 2003). For the example of switchgrass it has been shown that the fibrous nature of grass leads to higher specific energy consumption for grinding than other herbaceous biomass (Mani et al., 2004). Specific energy consumption for grass comminution

Table 3
Effects of leaching on concentrations of ash and selected elements in grass.

Grass	Leaching treatment	Ash	N	S	K	Cl	Reference
		[% in DM]					
Extensive grassland	Without		1.38	0.20	1.53	0.81	Kasper (1997)
	Sprinkling 40 mm (2 × 20 mm)		1.36	0.21	1.00	0.66	
	Sprinkling 100 mm (5 × 20 mm)		1.14	0.18	0.86	0.31	
Banagrass	Without	3.94	0.60	0.10	n.r.	0.58	Turn et al. (1997)
	Initial dewatering press	3.05	0.48	0.06	n.r.	0.29	
	Multi-step dewatering (initial dewatering press, water rinse, secondary dewatering press)	2.69	0.41	0.05	n.r.	0.09	
	Coarse comminution and multi-step dewatering	2.66	0.31	0.05	n.r.	0.02	
Switchgrass	Without	3.77	0.31	0.08	0.04	n.r.	Jenkins et al. (1997)
	Laboratory washed	3.25	0.17	0.03	n.r.	n.r.	

Table 4
Bulk density, energy density and storing volume of grass biomass (Kasper, 1997; Lötjönen, 2008).

	Bulk density [$kg_{DM}\ m^{-3}$]	Energy density [$GJ\ m^{-3}_{DM}$]	Required specific storing volume [$m^3\ GJ^{-1}$]
Chopped grass	20–70	0.34–0.85	2.94–1.18
Large round bales	80–150	1.36–2.55	0.39–0.74
Large square bales	140–170	2.38–2.89	0.35–0.42
Compact bales	200–300	3.40–5.10	0.20–0.29
Briquettes, pellets	350–500	5.10–10.20	0.10–0.20

increases with decreasing particle size (Igathinathane et al., 2008; Mani et al., 2004).

3.2.2. Compression

Techniques to compress grass biomass normally comprise baling, briquetting, and pelleting and in that increasing order to achieve bulk density (Table 4), as well as equipment complexity, energy requirement, and costs (Werther et al., 2000). Compression of biomass into pellets or briquettes improves physical homogeneity, increases bulk and energy density, improves ease of handling, and flow properties (Kaliyan and Morey, 2009; Mani et al., 2006). The technologies have been commonly used for decades, since pelleting is widespread for producing animal feed and briquetting for compressing coals, minerals, and metals (Kaliyan and Morey, 2009). The process comprises pre-treatment such as grinding, drying, mixing with additives if necessary, and the actual compression. Compressing occurs through pressing the feed material through dies by rollers for pelleting or extruders for briquetting (Kaliyan and Morey, 2009; Larsson et al., 2008).

High energy density, high strength and durability are the main aims of compression. Success mainly depends on particle size, compression force, moisture content, and on natural or added binders (Kaliyan and Morey, 2009; Mani et al., 2006). Pelleting and briquetting should consume least possible energy and must be economically justifiable (Werther et al., 2000).

3.3. Firing

Grass combustion is possible as stand-alone biomass-firing or co-firing with other fuels such as coal, natural gas, peat, or wood. Scale of biomass combustion ranges from heat supply in private households with 10–100 kW_{th} via district heating with plant capacities of 0.5–10 MW_{th} to combined heat and power plants up to a capacity of 80 MW_{th} in most cases (Obernberger, 1998; Werther et al., 2000).

The two most common boiler types for biomass combustion are grate-firing systems and fluidized bed combustors. Main characteristics can be summarized as follows (Khan et al., 2009; Obernberger, 1998; Werther et al., 2000; Yin et al., 2008): both have good fuel flexibility and can be fuelled entirely by biomass or co-fired with coal. Capacities of grate-fired boilers range from smaller than 1 MW to 300 MW_{el} in biomass-fired combined heat and power plants. Furnace temperature should not exceed 900 °C for normal operation. Water-cooled moving-grate systems are preferred. Advantages of grate-firing systems are insensitivity to fuel bed agglomeration, good operation at partial loads, low nitrogen oxide emissions by using advanced secondary air systems, very low dust load in flue gas, medium to low capital costs, and medium to very low operation and maintenance costs. Problems comprise higher needs of adjustment to fit a particular fuel, combustion instabilities in the fuel bed, and high levels of incompletely burned carbon in the fly ash. Fluidized bed boilers are considered as mature technologies, beginning at a capacity of 10 MW_{th} for bubbling fluidized bed combustion and 30 MW_{th} for circulating fluidized bed combustion. Temperature normally varies between 800 and 900 °C. The main advantages of fluidized bed combustion are uniform temperature distribution, large solid–gas exchange area, high heat transfer coefficients between bed and the heat exchanging surfaces, and stable combustion operation at low temperatures. Nitrogen oxides can be kept low by air staging and sulfur oxide emissions by sulfur capture with additives. The disadvantages include defluidization problems due to agglomeration of bed materials, requirement of highly efficient gas–solid separation systems, high erosion rates of boiler internals due to high solid velocities, and high dust load in the flue gas. Partial load operation requires special technology. Fluidized bed combustion is more expensive.

Biofuel characteristics of herbaceous biomass require various specific adaptations of the different combustion technologies (Khan et al., 2009; Lewandowski and Kicherer, 1997; Obernberger, 1998; Werther et al., 2000; Yin et al., 2008):

- for achieving a more complete combustion (grate-firing systems): advanced air supply systems, optimized grate systems, sufficient residence time;
- for nitrogen oxide emission reduction: appropriate air and fuel staging, steam air recirculation, selective catalytic or non-catalytic reduction;
- for sulfur oxide emission reduction: sulfur fixation in the ash, addition of limestone or dolomite, efficient technology for dust precipitation;
- for reduction of deposits and corrosion: increasing the melting point of the ash by capture of alkali compounds with different additives;
- for control of agglomeration (fluidized bed combustion): increasing the melting temperature of sintering compounds by co-combustion with clean fuels, use of additives, and use of alternative bed materials;
- for dust emission reduction: efficient aerosol precipitation and further treatment (electrostatic precipitators and bag house filters).

Herbaceous biomass can be fired as bales (whole or sliced), as loose material (chopped, shredded, or milled), as briquettes, and as pellets. Each of these fuel types requires specific delivery and furnace technology according to the form and size of biomass bulk (Obernberger, 1998; Yin et al., 2008).

Co-combustion of biomass commonly occurs in practice today (Khan et al., 2009). Several technology options exist for co-firing (Tillman, 2000): blending the biomass with coal on the fuel pile is the first and least cost approach, however, the percentage of biomass that can be added is very limited. Separately preparing and injecting the biomass into the boiler has been readily managed in demonstration projects and practice. Gasifying the biomass for subsequent firing in an electricity generating system permits the use of biomass in natural gas-fired systems. Several modifications of the fuel preparation and firing process might be necessary for co-combustion (Baxter, 2005; Werther et al., 2000).

4. Economy

4.1. Profitability

One precondition for the implementation of grassland biomass combustion in practice is that revenues exceed costs. Regarding grass as a solid biofuel costs arise from biomass supply and

Table 5
Economic parameters of permanent grassland biomass for combustion.

Grasses	Economic parameter	Unit	Value	Remarks	Reference
Extensive meadow				One cut per year, no establishment, no fertilization, yield 3.9 t_{DM} ha^{-1} a^{-1}	Rösch et al. (2007)
Round bales of hay	Supply costs	€ t_{FM}^{-1}	110–145		
	Supply costs	ct kWh^{-1}	2.7		
	Heat generation costs	ct kWh^{-1}	9.1–9.8		
Square bales of hay	Supply costs	ct kWh^{-1}	2.9		
Hay pellets	Supply costs	ct kWh^{-1}	5.2		
	Heat generation costs	ct kWh^{-1}	10.2		
Miscanthus				16 years, yield 14 t_{DM} ha^{-1} a^{-1}, production costs and gross margin discounted and annualized	Styles and Jones (2008)
Chopped	Production costs	€ t_{DM}^{-1}	43		
	Gross margin	€ ha^{-1} a^{-1}	383		
Baled	Production costs	€ t_{DM}^{-1}	48		
	Gross margin	€ ha^{-1} a^{-1}	326		
Miscanthus (baled)	Breakeven farmgate price	$ t_{DM}^{-1}	42	Miscanthus lifetime 20 years, yield 35.8 t_{DM} ha^{-1} a^{-1}, switchgrass lifetime 10 years, yield 9.4 t_{DM} ha^{-1} a^{-1}, round trip distance 128 km, breakeven price: price needed to offset discounted and annualized production costs	Khanna et al. (2008)
	Breakeven delivered price (excluding land rent)	$ t_{DM}^{-1}	50		
	Breakeven delivered price (including opportunity costs of land)	$ t_{DM}^{-1}	59		
Switchgrass (baled)	Breakeven farmgate price	$ t_{DM}^{-1}	57		
	Breakeven delivered price (excluding land rent)	$ t_{DM}^{-1}	65		
	Breakeven delivered price (including opportunity costs of land)	$ t_{DM}^{-1}	98		
Reed canary grass				Yield 6 t_{DM} ha^{-1} a^{-1}, transport distance 70 km	Lindh et al. (2008)
Baled, mobile crusher	Production costs	ct kWh^{-1}	2.8		
Chopped, loose	Production costs	ct kWh^{-1}	2.6		
Reed canary grass	Breakeven farmgate price	ct kWh^{-1}	0.6–1.3[a]	Yield 7 t_{DM} ha^{-1} a^{-1}, different subsidy schemes and crops to be replaced	Larsson (2006)
Reed canary grass (baled)	Production costs	$ ha^{-1} a^{-1}	522–606	Yields 8.2–10.9 t_{DM} ha^{-1} a^{-1}, transport distance 48 km	Hallam et al. (2001)
	Delivered breakeven price	$ t_{DM}^{-1}	48–74		
Switchgrass (baled)	Production costs	$ ha^{-1} a^{-1}	451–530	Yields 11.1–11.6 t_{DM} ha^{-1} a^{-1}, transport distance 48 km	
	Delivered breakeven price	$ t_{DM}^{-1}	39–48		
Big bluestem (baled)	Production costs	$ ha^{-1} a^{-1}	489–569	Yields 9.5–8.8 t_{DM} ha^{-1} a^{-1}, transport distance 48 km	
	Delivered breakeven price	$ t_{DM}^{-1}	56–59		

[a] Figures converted from Swedish Krones.

combustion, while revenues result from the sale of biomass and possibly subsidies for land use. Costs for biomass supply comprise costs for grassland management, harvest, storage, handling, processing, overhead costs, and opportunity costs. They vary in a wide range (Table 5) and depend mainly on yields and harvesting technologies. In extensive permanent meadows, where input is at a minimum since it consists only of harvest, transport, and storage, however costs per unit product are high due to extremely low yields (Rösch et al., 2007). For perennial energy grasses biomass yields are much higher. Although costs for crop establishment and fertilization arise additionally harvest still remains the most expensive annual operation (Khanna et al., 2008; Styles and Jones, 2008). Optimization of the logistic chain, including harvest, transport, storage, and processing, can make remarkable contributions to cost reduction (Cundiff, 1996; Cundiff and Grisso, 2008; Lindh et al., 2008; Styles and Jones, 2008).

Combustion costs comprise fixed and variable costs for the firing plant, labour costs, and overhead costs. Mainly they depend on the size and technical design of the plant. Accounting for 5-7 ct kWh^{-1} for grass the percentage of combustion costs in heat generation costs is 25–50% and, thus, often much higher than the costs for biomass supply (Rösch et al., 2007).

In contrast to biogas production, where farmers often act as biomass producers and biogas plant operators at once and thus receive income from the sale of energy (for details see Prochnow et al., 2009), biomass combustion is mainly practiced in large central firing plants or in private households. The sale of biomass to firing plants or other purchasers is the main source of income when producing solid biofuels, possibly complemented by payments for land use. Hence, market prices for grass as a solid biofuel are crucial for profitability. They depend on market prices for the fossil fuels grass is expected to substitute, i.e. heating oil, natural gas, coal, and peat. Given a price of reed canary grass at the power plant of 38 € t^{-1} and farming subsidies of 593 € ha^{-1}, solid biofuel production in Finland is economically feasible depending on transport distance in combination with harvesting, processing and transport technology (Lindh et al., 2008). Under German conditions, including farming and environmental payments, hay pellets from extensive permanent meadows could compete against heating oil at heating oil prices above 60 ct l^{-1} (Rösch et al., 2007). In Illinois the breakeven cost of miscanthus and even more of switchgrass for electricity generation is considerably higher than the coal energy-equivalent biomass price of 20.22 $ t_{DM}^{-1}. The production of perennial energy grasses in Illinois or their use for co-firing with coal by power plants or both would have to be subsidized, preferentially by regulation related to the environmental benefits (Khanna et al., 2008). Incorporating nonmarket values into feedstock costs, energy from switchgrass would be highly competitive against fossil fuels. These values include direct economic benefits to the farm economy, other indirect economic benefits associated with crop pricing and subsidy payments, ecological benefits from improved soil and water quality, and reduced greenhouse gas emissions. Net benefits to society are estimated at 44.9–60.7 $ t_{DM}^{-1}, resulting from increased farm revenues of 37.5–40.4 $ t_{DM}^{-1}, reduced government subsidies of 25.5 to 36.4 $ t_{DM}^{-1} and reduced carbon emissions of 16 $ t_{DM}^{-1} less increased consumer costs of 26.7–46.5 $ t_{DM}^{-1} (McLaughlin et al., 2002).

4.2. Competitiveness

From an economic point of view grassland biomass for combustion competes not only with fossil fuels, but also with forage supply for animal husbandry, in the case of perennial energy grasses as well as with conventional and with other bioenergy crops, and with other ways of energy or material use of grass.

Regarding competition between forage and bioenergy in developed countries a growing production of milk and meat is achieved with decreasing ruminant numbers, resulting in an increasing amount of surplus grassland with remarkable bioenergy potential, while in emerging and developing countries a rapidly rising demand for and production of milk and meat induce growing pressure on grasslands, so that their use for animal feed presumably will take priority over use for bioenergy (for details see Prochnow et al., 2009). With respect to competition of perennial energy grasses against other crops miscanthus compares favorably on a gross margin basis with conventional agricultural systems such as cattle rearing, sugar beet, winter wheat, spring barley and set aside in Ireland (Styles and Jones, 2008). An economic analysis from the United States concludes that at a farmgate price of 30 $ t^{-1} switchgrass could potentially be produced at a greater profit than traditional crops on $4.23 \cdot 10^6$ ha and at a farmgate price of 40 $ t^{-1} on $9.46 \cdot 10^6$ ha (Walsh et al., 2003).

Competitiveness with wood as an alternative biomass feedstock for combustion strongly depends on yields. Economic calculations for switchgrass in the United States and miscanthus in Ireland show that these perennial energy grasses with their high yields are relatively more profitable than short-rotation coppice from poplars or willows (Styles and Jones, 2008; Walsh et al., 2003), while heat generation costs from hay pellets from low-yielding extensive meadows in Germany are higher than those from short-rotation poplar chips of 6.9–8.5 ct kWh^{-1} (Rösch et al., 2007).

Among the possible energy uses of grass currently biogas production and combustion can be found in practice. Both systems are hardly comparable. First, different grassland management intensities lead to biomass characteristics which make the grass suitable either for anaerobic digestion or for combustion, more or less excluding the other way of use. Second, grass as feedstock for biogas production as a rule is co-digested with other feedstock, which primarily decide on profitability of the entire process. This makes it difficult to separate the grass and to compare with grass as a solid biofuel that is co-fired with fossil fuels or fired alone. Third, different subsidy schemes exist for biogas production and combustion. Assuming grassland management intensity adapted to natural site conditions anaerobic digestion and combustion of grass, rather than compete, complement one another.

5. Environmental impacts

5.1. Biogeochemical cycles

5.1.1. Carbon

For a general overview on carbon cycling in grasslands see Soussana et al. (2004), for a specific comparison of carbon cycling in animal husbandry and bioenergy production via anaerobic digestion see Prochnow et al. (2009). A principal difference of biomass use for combustion consists in the fact that nearly none of the carbon removed from the field remains for return. The amount of carbon removed can range from 450 kg ha^{-1} a^{-1} in semi-natural grasslands to about 15,000 kg ha^{-1} a^{-1} in high-yielding perennial grasses. During combustion the major part of the biomass carbon reacts to gases, above all to carbon dioxide, partly to carbon monoxide as a product of incomplete combustion, and organic compounds in the gaseous phase (Khan et al., 2009; Yin et al., 2008; Werther et al., 2000). The other part of the biomass carbon is bound into the ash within organic compounds and carbonates. Due to lacking data for ash fraction percentages and carbon contents in grass ashes figures from straw ashes are used. Bottom ash and cyclone fly ash as the only ash fractions suitable for application on agricultural land has a percentage of 80–90% in total ash and contains about 8–90 g kg_{DM}^{-1} of organic carbon and 4 g kg_{DM}^{-1} of carbonate carbon (Obernberger et al., 1997). Based on fuel ash contents of 2–12% in grasses (Table 1) a negligible portion of about 0.1–1% of the biomass carbon removed at harvest would theoretically be available for return to the grassland. Thus, in contrast to animal husbandry and biogas production, where 17–72% of the biomass carbon cycle within in the grassland system (Prochnow et al., 2009), biomass use for combustion means that all carbon removed from the field is equally exported from the grassland system.

Depending on the level of biomass production the portion of carbon fixed from the air that is stored in belowground biomass and soil can compensate for or even succeed carbon exports. Soil organic carbon accumulation rates of 30–1100 kg ha^{-1} a^{-1} are reported for permanent grasslands dependent on productivity (Post and Kwon, 2000). Under conditions of low productivity long periods are needed for pronounced increases in soil organic carbon. Plots with low input and a high diversity of native grassland species in the United States had a total carbon dioxide sequestration rate of 4400 kg ha^{-1} a^{-1} in roots and soil to a depth of 0.6 m during the decade after establishment (Tilman et al., 2006). Positive effects of high plant diversity on short-term carbon storage are reported from a four-year experiment in Germany (Steinbeiss et al., 2008). Results from perennial energy grasses suggest the potential for storing a significant quantity of soil carbon for switchgrass (Frank et al., 2004; Garten and Wullschleger, 2000; Liebig et al., 2005) and miscanthus (Zan et al., 2001). Thus, high productivity permanent grasslands that provide solid biofuel have a remarkable potential for carbon sequestration.

5.1.2. Nutrients

Nitrogen by far is the dominant nutrient constraint on primary production of most grasslands. For a general overview on nitrogen cycling in grasslands see Wedin and Russelle (2007), for a specific comparison of nitrogen cycling in animal husbandry and bioenergy production via anaerobic digestion see Prochnow et al. (2009). When using grass biomass for combustion nitrogen removed at harvest completely leaves the grassland system. The amount of nitrogen removed can range from 15 kg ha^{-1} a^{-1} in semi-natural grasslands to about 300 kg ha^{-1} a^{-1} in high-yielding perennial grasses. During combustion all biomass nitrogen forms gases such as molecular nitrogen and nitrogen oxides, among these mostly nitric oxide, smaller amounts of nitrogen dioxide, and negligible quantities of nitrous oxide in most combustion systems (Glarborg et al., 2003; Werther et al., 2000). The amount of nitrogen in biomass ash is negligible. Since no figures for herbaceous biomass are available, contents of 0.6-0.9 g kg^{-1} in wood ash might be cited here (Demeyer et al., 2001). Thus, no biomass nitrogen removed with harvest can be returned to the grassland. Such negative consequences for the nitrogen cycle and for primary production can generally be compensated by the addition of mineral fertilizer and by symbiotic nitrogen fixation (Soussana et al., 2004). Nitrogen fixation by forage legumes in grasslands usually ranges from 50 to 200 kg ha^{-1} a^{-1} (Wedin and Russelle, 2007). In low-input grassland with a diverse mixture of native grassland species in the United States nitrogen provision only by legumes allowed to achieve considerable energy yields and carbon sequestration (Tilman et al., 2006). Even for monocultures of perennial energy grasses, the recommended levels of nitrogen fertilization are moderate. After establishment a level of about 50 kg ha^{-1} a^{-1} on poor soils is recommended for switchgrass, miscanthus, and reed canary grass, while on more fertile soils nitrogen fertilization is not effective (Lewandowski et al., 2003b). Late harvest of grasses not only improves biofuel quality, it also reduces nitrogen removal and demand for substitution by mineral fertilization (Hadders and Olsson, 1997; Landström et al., 1996; Reynolds et al., 2000).

Other plant nutrients such as phosphorus, potassium, magnesium, and sodium, are nearly completely recovered in the agriculturally usable ash-mixture of bottom ash and cyclone fly ash (Obernberger et al., 1997). Thus, returning the ash to the grassland could close the cycles of these nutrients. However, so far there is no experience with ash application on grasslands.

5.1.3. Greenhouse gases

A substantial greenhouse gas reduction potential of grassland biomass combustion is reported for low-input permanent grassland as well as for perennial energy grasses (Table 6) (Lewandowski and Heinz, 2003; Rösch et al., 2009; Styles and Jones, 2007; Tilman et al., 2006). Reduction potentials vary depending on the total greenhouse gas emissions from land use and biomass conversion and on the potential sources of greenhouse gas savings, comprising of substitution of fossil energy, mitigation of emissions from animal husbandry and carbon sequestration in soil and roots.

Greenhouse gas emissions from land use, including direct and indirect emissions, and emissions from soil and animals, are low for energy grass cultivation compared with animal husbandry. While miscanthus cultivation is responsible for 1938 kg $CO_{2eq.}$ ha^{-1} a^{-1}, dairy systems emit 12,068 kg $CO_{2eq.}$ ha^{-1} a^{-1}, and sheep 3751 kg $CO_{2eq.}$ ha^{-1} a^{-1} (Styles and Jones, 2007). The combustion process, setting free nitrous oxide and methane, contributes only a third to the total greenhouse gas emissions of the entire solid biofuel chain of miscanthus (Styles and Jones, 2007). The carbon dioxide emissions during biomass combustion are not considered greenhouse gases, since they originate from recent carbon. In contrary to this, the carbon dioxide emissions during coal combustion dominate greenhouse gas burdens of this fossil fuel. The greenhouse gas reduction potential of miscanthus replacing coal accounts for 25,080 kg $CO_{2eq.}$ ha^{-1} a^{-1} (Styles and Jones, 2007). Summing up the reduction potentials by substituting fossil fuel and animal husbandry, miscanthus can save up to 35,209 kg $CO_{2eq.}$ ha^{-1} a^{-1} (Table 6). The reduction potential of firing biomass from low-input grassland, meaning zero nitrogen fertilization, is estimated at 10,000 kg $CO_{2eq.}$ ha^{-1} a^{-1} for a mixture of native grassland species established on fallow land in the United States (Tilman et al., 2006) and about half of this for permanent grassland in Germany (Rösch et al., 2009). The variance of the reduction potentials results from different yields, inputs and greenhouse gas saving components included into the calculations. Comparing biogas and combustion as two bioenergy production chains from grassland, the greenhouse gas reduction potential is at about the same level (Rösch et al., 2009).

Table 6
Greenhouse gas reduction potentials by using permanent grassland biomass for combustion.

Type of grassland	Type of fossil energy (and if regarded land use) replaced	Greenhouse gas reduction [kg $CO_{2eq.}$ ha^{-1} a^{-1}]	Reference
Low-input permanent grassland (biomass yield 3.9 t_{DM} ha^{-1} a^{-1})			
Hay bales	Crude oil	4407–4541	Rösch et al. (2009)
Hay pellets	Crude oil	5125	
Low-input high-diversity permanent grassland (bioenergy yield 68.1 GJ ha^{-1} a^{-1})	Coal	10,000	Tilman et al. (2006)
Miscanthus (biomass yield 11.7 t_{DM} ha^{-1} a^{-1})	Coal	25,080	Styles and Jones (2007)
	Coal and dairy	35,209	
	Coal and cattle	28,378	
	Coal and sheep	26,893	

5.2. Biodiversity

Biodiversity in grasslands largely is a result of management practices. Low mowing frequencies and fertilization levels enhance biodiversity (for details see Prochnow et al., 2009). The extensive grassland management necessary for solid biofuel production meets the management requirements of many semi-natural grassland types, where high biodiversity coincides with low agricultural input. Semi-natural grasslands belong to the hot spots of biodiversity in rural areas (European Environment Agency, 2004). Declining dramatically during the last decades due to intensification or abandonment, they are given conservation priority today. Solid biofuel production could be a sound option to keep semi-natural grasslands in an appropriate, biodiversity-friendly use.

Once established, perennial energy grasses are characterized as well by a rather extensive management with little land disturbance, low mowing frequency and low levels of fertilization and pesticide application. Results of hitherto existing research indicate that the impacts of perennial energy grass cropping on biodiversity depend to a large extent on vegetation structure (height, density, uniformity). Species richness in young stands of perennial energy grasses is higher than in common crops such as wheat (Bellamy et al., 2009), but lower than in field margins. A mature and well established crop with a closed canopy cover is on par with arable crops (Semere and Slater, 2007a,b). Replacing ex-arable crops with perennial energy grasses is anticipated to be advantageous for biodiversity, a large proportion of young stands preconditioned (Semere and Slater, 2007a). Agri-environmental measures are suggested to optimize large-scale energy grass cropping and to maintain the biodiversity benefits of young stands in the mature crop, such as using seed mixtures to establish diverse vegetation in the entire field (Tilman et al., 2006) or in the headlands (Bellamy et al., 2009), leaving patches unplanted within the fields (Bellamy et al., 2009), or leaving strips or fields unharvested each year (Murray et al., 2003; Roth et al., 2005).

Overall, solid biofuel production from permanent grassland has a potential for predominantly positive impacts on biodiversity.

5.3. Water quality

The principal functions of grasslands for surface water quality by protecting the soil from erosion as well as for ground water formation and quality will remain when using it for bioenergy production (for details see Prochnow et al., 2009). Moreover, solid biofuel production can be expected to yield further benefits for water quality due to the extensive grassland management with low levels of fertilization and risk of leaching and hardly ever activities that could contribute to soil erosion.

6. Conclusions

Using grassland biomass for combustion is a subject of broad research and established in practice. An extensive grassland management with one late cut per year and low levels of mineral fertilization is required to achieve best possible fuel quality. Conventional farm machinery is used for grass harvest. Biofuel quality can be improved by pelleting or briquetting. Combustion technology needs various adaptations to the difficulties caused by biofuel properties of grass.

Profitability of solid biofuel production from grassland biomass can be achieved at supply and combustion costs in the lower range and sufficient income from biomass sale and subsidies for land use. Environmental benefits arise from the mitigation of greenhouse gas emissions, and positive effects on biodiversity and water quality due to extensive grassland management. Special attention has to be given to the compensation of the complete exports of carbon and nitrogen in the biomass harvested. A sufficient nitrogen supply provided by legumes or moderate mineral fertilization allows to produce enough biomass to replace or even accumulate carbon.

The following issues are considered to be of further research interest on solid biofuels from grassland:

- extension of the so far few attempts to model fuel quality,
- targeted application of precipitation during field period after mowing for leaching of undesired elements,
- improving harvesting technology and logistics,
- further adaptation of combustion technology to grass biofuel characteristics,
- comprehensive economic assessment at the scales of processes, farms and regions, covering the whole chain from solid biofuel supply to combustion and energy use,
- comprehensive life cycle assessment, focussing on greenhouse gas emissions, carbon and nutrient cycles, and biodiversity, comparing solid biofuel use to alternative grassland uses.

Grass species
Banagrass *Pennisetum purpureum*
Big bluestem *Andropogon gerardii*
Coastal panic grass *Panicum amarum*
Cocksfoot *Dactylis glomerata*
Giant reed *Arundo donax*
Indiangrass *Sorghastrum nutans*
Meadow foxtail *Alopecurus pratensis*
Miscanthus *Miscanthus sinsensis, Miscanthus x giganteus*
Reed canary grass *Phalaris arundinacea*
Switchgrass *Panicum virgatum*

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