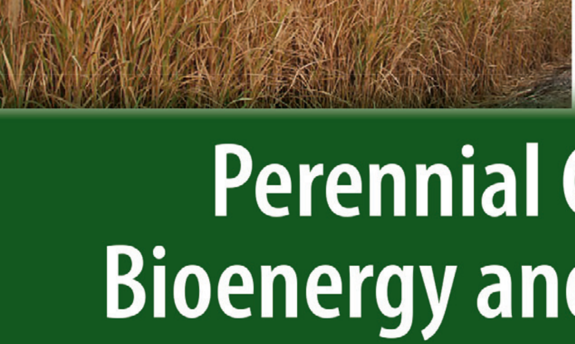
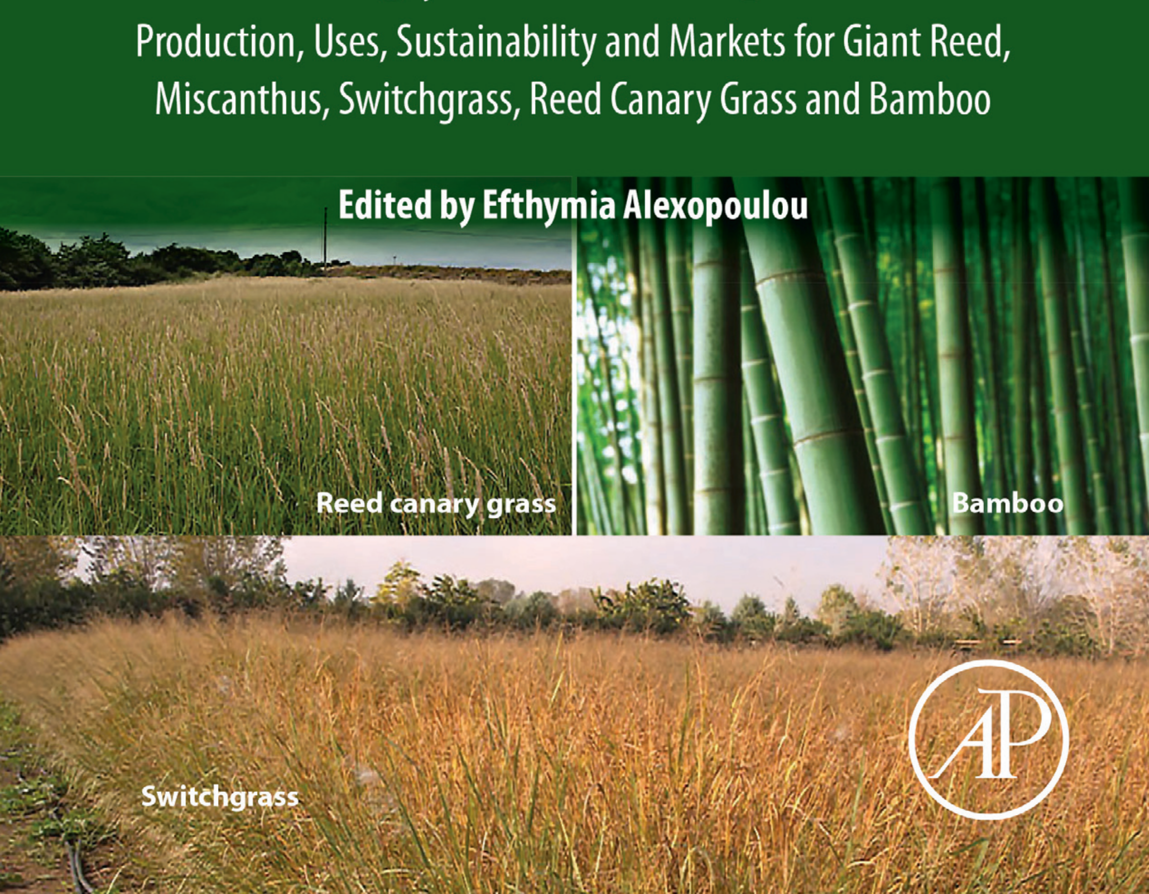
Perennial Grasses for Bioenergy and Bioproducts

Production, Uses, Sustainability and Markets for Giant Reed, Miscanthus, Switchgrass, Reed Canary Grass and Bamboo

Edited by Efthymia Alexopoulou





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CRES, Center for Renewable Energy Sources and Saving, Pikermi, Attikis, Greece

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Introduction

Perennial grasses are considered as an ideal feedstock for **bioenergy** and **bioproducts**. In general, perennial grasses are drought-resistant crops and recently have been attracting growing interest due to their extensive environmental benefits at both global- and agricultural community scales. Compared to traditional row crops, perennial grasses in general require lower energy inputs (fertilizers, pesticides, etc.), can be grown on marginal cropland, and provide benefits in terms of soil structure and stability (e.g., reduced soil loss, erosion, and runoff), soil quality (e.g., increase in soil fertility, organic matter, and nutrient retention), and biodiversity (e.g., cover for native wildlife). Perennial grasses are also not seen as competing for agricultural land because they can be grown on marginal or degraded lands where intensive agricultural practices harm the environment (e.g., promoting soil erosion), and where the economic returns for the farmer's labor and capital are not sustainable.

Perennial Grasses for Bioenergy and Biobased Products presents the importance of perennial grasses in eight chapters. The book starts with the importance of perennial grasses as a feedstock for bioenergy and bioproducts (Chapter 1) and continues with five chapters that each deals with one perennial grass, namely, **giant reed** (Chapter 2), **miscanthus** (Chapter 3), **switchgrass** (Chapter 4), **reed canary grass** (Chapter 5), and **bamboo** (Chapter 6). The products and markets of perennial grasses are presented and discussed in Chapter 7, while their sustainability is analyzed in Chapter 8.

Chapter 1 describes the increasing importance of perennial grasses as a biomass source for both energy and nonenergy applications in Europe. Special emphasis is given to the current legislation on renewable energy and concerns the use of food crops for first-generation biofuels production that led to the foods versus fuels debate, land use change scenarios, and other environmental concerns. Perennial grasses are lignocellulosic, low-cost feedstock, able to grow in various environments and to thrive on marginal lands. They have been indicated as leading candidate feedstock for modern biobased economies to produce a number of high-added value products (i.e., biopharmaceuticals, nutrient supplements, and biopolymers), biomaterials (i.e., building products, phonic insulating materials, and mulching and biodegradable products for gardening and animal bedding), energy carriers (advanced biofuels, heat, and power), and by-products (i.e., soil organic fertilizer and green chemistry products). However, research is still needed in breeding, agronomy, postharvest logistics, and bioconversion to deliver new elite varieties to expand the European market and reach potential yield and desired biomass quality, while maximizing conversion efficiencies.

Miscanthus, a C_4 grass native to East Asia, is a leading perennial biomass grass in Europe which possesses high dry matter yield potential, resource use efficiency, and the ability to grow under a wide range of climatic conditions. Chapter 2 provides an overview of the genetic background, breeding, and agronomy of miscanthus. It focuses on a description of the complete miscanthus-based production and value chain from the provision of genetic material through to biomass production and potential uses. The suitability of miscanthus biomass for energy uses (e.g., combustion, biogas, and liquid fuels), material and chemical uses (e.g., building materials and animal bedding), and food use is discussed. The environmental performance of miscanthus production is also outlined, including aspects of biodiversity, soil restoration, and life cycle assessment. Finally, miscanthus production costs and carbon mitigation are considered.

Switchgrass is a C_4 warm-season perennial grass that at the beginning of 1980s was selected as an ideal energy crop for the United States. A decade later it was adopted by Canada and Europe as a promising high-yielding lignocellulosic crop that could be cultivated on marginal land. Chapter 3 summarizes the knowledge that has been collected on the crop so far at a world level, covering the whole production chain. Although several breeding programs have been carried out in the United States, switchgrass is still considered primarily as an undomesticated plant with great potential for agronomic and biofuel trait improvements. The crop is established by seed and there are a large number of available varieties (lowland and upland ones) covering latitudes from Mexico to far North America. Successful establishment is a key factor for the crop to achieve high yields and to ensure a lifespan longer than 15 years. When switchgrass has successfully been established the celling yields could be anticipated as early as the second or third year. Although in most research work the lowland varieties (e.g., Alamo and Kanlow) have been reported as more productive than the upland varieties (e.g., Blackwell and CIR), selection of the appropriate variety should be closely related to the site-specific pedoclimatic conditions. Nitrogen fertilization should be avoided at the establishment year but should be applied from the second year and thereafter on an annual basis. Most research work agrees that the final harvest should be done a few weeks after a killing frost (winter). The harvested biomass is characterized by a high portion of leaf material (around 40%), while its moisture content could be quite low (around 20%). The lignocellulosic biomass of switchgrass is suitable for energy production through thermochemical (gasification, combustion, and pyrolysis) and biochemical (advanced biofuels: bioethanol and biogas) processes. Last but not least, switchgrass feedstock could be used for bioproducts and biomaterials production.

Giant reed (*Arundo donax* L.) is a C_3 perennial rhizomatous grass belonging to the Gramineae family. Originating in Asia it later spread to different subtropical wetlands and warm-temperature regions of Europe, Africa, North America, and Oceania. Chapter 4 summarizes the knowledge that has been collected on the crop so far at a world level, covering the whole production chain. A wide range of yields is reported in the literature depending on the site, climate, soil type and fertility, inputs, cultivation and harvest practices, and age of plantation. Giant reed has an uncommon high photosynthetic capacity as compared to other C_3 species, and is very similar to those of C_4 species. It is able to achieve high photosynthetic rates up to ~38 μmol $CO_2\,m^{-2}\,s^{-1}$ in well-watered treatments, but with substantial transpiration, leading to low, or at least lower, water use efficiency than many C_4 crops (1.19–2.47 $g\,kg^{-1}$), but still more efficient than most C_3 species. The response of giant reed to N fertilization is expected to be minimal or even zero, as long as the soil nitrogen availability, rhizomes reserves, and other N inputs are sufficient to supply the uptakes. On the other hand, irrigation plays a significant role in increased dry matter yields, being 30.0%–40.0% higher in well-watered than rainfed conditions. However, giant reed can also be considered as a drought-resistant crop. The choice of a harvest method over another is determined by several parameters, such as crop status, biomass moisture content at harvest, logistics, availability of equipment and type of storage, required biomass quality, and final use. Fuel characteristics of the harvested material, such as calorific value (17–18.8 MJ), ash (5.3%–8.1%) content of stems as well as its cellulose (43.4%), hemicellulose (25.1%–29.2%), and lignin (10.6%) content can be considered satisfactory for the production of energy, biogas, advanced biofuels, paper, and pulp. Recently, interest has focused on the production of fuels, chemicals, and other products of high added value within a multiproduct biorefinery.

The perennial reed canary grass (RCG) offers considerable potential as a bioenergy crop, including on marginal land. The knowledge that has been collected on the crop so far at a world level, covering the whole production chain, is presented in Chapter 5. It can be harvested for combustion, anaerobic digestion, pyrolysis, gasification, and cellulosic ethanol production, and therefore also has potential for bioplastic production. It is a widely adapted temperate grass that is broadly tolerant of many stresses including flooding, drought, freezing, and grazing. RCG is found in a wide array of habitats, including wetlands, riparian zones, stream banks, irrigation channels, roadsides, forest margins, pastures, and disturbed areas, and has shown potential in diverse phytoremediation studies. RCG has a number of attributes that combine to make it a unique crop with an important role to play in the mix of energy crops grown in multiple geographies. This chapter reviews the many uses of RCG in the developing bioeconomy, highlighting the potential of this native European and North American crop in the future delivery of sustainable fossil fuel alternatives.

Bamboo (Chapter 6) is a versatile and widely utilized plant, with many traditional applications including edible shoots, toothpicks, chopsticks, crafted baskets and mats, tools, musical instruments and artwork, horticultural crop support sticks, fuel, erosion control and soil protection, housing construction material, and fuel. This chapter reviews the bamboo properties that are favorable for a wide range of applications in modern food and biobased industries, ranging from paper and pulp, dietary fiber food additives, textiles, biochemicals, or renewable bioenergy. The state of the art of technical development and innovations and constraints for bamboo production are described. Bamboo is considered to be an ideal crop for rural development in developing countries. Bamboo production and utilization are considered relevant to many of the UN sustainable development goals. The potential of this abundant CO_2 neutral resource is explored to supply future generations with essential products and basic needs.

Chapter 7 describes the suitability of lignocellulosic perennial grasses to thermochemical and biochemical processes for energy application, and other alternative uses toward the biobased economy in Europe. Perennial grasses are herbaceous, lignocellulosic plants. Their chemical composition is made up primarily of structural polysaccharides, namely, celluloses and hemicelluloses, of lignin, and of small fractions of nonstructural components, such as extractives, proteins, lipids, pectin, and ash. The recalcitrance of lignocellulosic material has been recognized as one of the most important sustainability characteristics of this plant type, since it contributes to the natural resistance to pests and diseases. However, the recalcitrance of the plant cell wall constrains the hydrolysis of structural carbohydrates for biochemical conversions, namely, second-generation bioethanol and anaerobic digestion. On the other hand, perennial grasses are suitable for thermochemical conversions; however, ash melting temperatures should be carefully evaluated for high-temperature processes. The main chemical composition and factors affecting perennial grass biomass quality are discussed, and examples of the most widely used bioconversion processes involving perennial grasses are reported.

Either for bioenergy or biomaterials, perennial crops offer environmental advantages by contributing to the reduction of greenhouse gases and energy use, and social benefits, especially in rural areas. However, their production cost is affected by yields that can compromise its economical exploitation. In this context, studies on the sustainability of perennial crops production are reviewed, taking into account environmental, economic, and socioeconomic aspects. In the end, a critical assessment of the literature is made providing hints on how the cultivation and use of perennial grasses can be promoted and managed envisaging gains in sustainability (Chapter 8).

The Importance of Perennial Grasses as a Feedstock for Bioenergy and Bioproducts

1

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1.1 Introduction

In a biobased economy context, steady interest is devoted to seeking the most suited bioenergy crop for a specific environment, with specific traits for end-use destination, high yield, and the ability to grow in degraded lands and to be highly competitive with food/feed crops. Perennial grasses for biomass production, such as miscanthus (*Miscanthus* spp.), reed canary grass (*Phalaris arundinacea* L.), switchgrass (*Panicum virgatum* L.), giant reed (*Arundo donax* L.), and bamboo (*Phyllostachys* spp.), among others, feature those characteristics typical of the ideotype of bioenergy crops.

This chapter describes the increasing importance of perennial grasses as a biomass source for both energy and nonenergy applications in Europe. Special emphasis is given to the current legislation on renewable energy and concerns regarding the use of food crops for first-generation biofuel production that led to food versus fuel debates, land use change scenarios, and other environmental concerns. Perennial grasses as the "ideotype" of bioenergy crops, bioenergy chains involving perennial grasses, environmental sustainability in a changing climate context, and future research perspectives to bring these species into cropping systems are also underlined.

Perennial grasses are high resource use efficient and high biomass yielding, and are suitable crops for adverse environmental conditions. Their nonedible nature made up primarily by hemicellulose, cellulose, and lignin makes their raw material a very attractive feedstock to produce advanced biofuels or biobased products, fitting the modern biobased economy criteria. As lignocellulosic feedstock, perennial grasses are expected to play an important role in achieving long-term goals for energy policy in cutting CO_2 emissions and contributing to the maintenance of energy supplies. Furthermore, perennial grasses might be grown on less productive cropland, providing benefits in terms of soil structure and stability (e.g., reduced soil loss, erosion, and runoff), soil quality (e.g., increase in soil fertility, organic matter, and nutrient retention), and biodiversity (e.g., cover for native wildlife), at both global and agricultural community scales.

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Perennial grasses have been widely used as fodder crops for centuries, often contributing significantly to energy supply on farms from animal power. There has been increasing interest in the use of perennial grasses as biomass crops in the United States and Europe since the mid-1980s (Lewandowski et al., 2003). From the beginning of the 1990s, several European projects investigated perennial grasses, i.e., Miscanthus productivity networks, Giant reed network, Switchgrass for Energy, Bioenergy Chains, 4FCROPS, and EUROBIOREF, among others (Alexopoulou et al., 2015). The European Commission has funded three research projects under the theme "KBBE.2011.3.1-02, Perennial grasses: optimising biomass production—SICA" with the aim of upscaling both cultivation and bioconversion techniques of perennial grasses, with special focus on marginal lands of south (OPTIMA, 289642), center (OPTIMISC, 289159), and north Europe (GrassMargins, 289461), whose main results can be found at the "Perennial Biomass Crops for a Resource Constrained World" conference proceedings (www.biomass2015.eu).

However, perennial grasses for biomass production are largely undomesticated plants, and are still at the early stages of development and improvement (Zegada-Lizarazu et al., 2010). Most of them are still in their wild form, collected from wild environments and tested in field trials, and hence at the very first stage of breeding programs. Thus proper varieties, their agronomic practices, and other postharvest logistics are still not optimized to reach their potential yield in a given environmental condition. Despite this, wild germplasms might conserve those traits of resistance and phenotypic plasticity with excellent adaptation strategies to overcome specific biophysical constraints typically encountered in marginal lands; furthermore, the use of wild germplasm well adapted to a given environment might serve as a source of genes for future breeding programs and in a context of climate change mitigation.

As bioenergy crops, however, they are required to reach the highest output (e.g., biomass yield, energy content) by minimizing both agronomic and other inputs (soil tillage, fertilization, irrigation, weeding and pest control, harvesting, transportation, storage, pretreatments, and bioconversion to energy use). Yet, a lot must be still done from a breeding point of view to improve the cultivation and postharvest techniques to exploit these species at the farm scale and to deliver "ideotypes" of bioenergy crop tailored for different European environmental conditions.

1.2 Increasing Interest for Perennial Grasses as a Biomass Source

The term biomass derives from the Greek *bio* meaning life + *maza* meaning mass, and refers to any biodegradable organic material originating from plants, animals, and microorganisms. Focusing on biomass originating from plants, it is referred to as any organic material built up from any plant of the kingdom Plantae directly via the photosynthetic conversion of solar energy, water, and carbon dioxide to produce carbohydrates and therefore chemical energy.

Renewable energy from biomass thus relies on the use of any organic material that is available on a renewable or recurring basis and used "as it is" or transformed into solid, liquid, or gaseous energy carriers thanks to the thermochemical or biochemical conversion of soluble and structural carbohydrates, lignin, proteins, fatty acids, and other chemical constituents (IEA, 2002).

Biomass to fuel fires is the oldest source of renewable energy, dating back a million years, likely as a discovery of our ancestor *Homo erectus* during the Early Stone Age. In Europe, traces of fire became evident only from around 400,000 years ago (Gowlett, 2016).

Prior to the development of coal, petroleum, and natural gas in the mid-19th century, nearly all forms of energy were renewable. During the industrial revolution, fossil fuels seemed to be the ideal and inexhaustible energy source. However, in the 1970s, the global energy and financial crisis inspired environmentalists to promote renewable energies as a replacement for the eventual depletion of and dependence on fossil oil. In addition, scientists brought to the community concerns around global warming, threats to the Earth's ozone layer, and environmental degradation.

In 1979, the first World Climate Conference established the World Climate Programme and the World Climate Research Programme. It also led to the creation of the Intergovernmental Panel on Climate Change and the United Nations Environment Programme in 1988.

Since that time, several assessment reports, negotiations, directives, and targets were set, with the aim of bringing to light environmental issues and promoting renewable energy (Table 1.1).

A key report was presented in 1987. The Prime Minister of Norway, Gro Harlem Brundtland, who chaired the World Commission on Environment and Development, presented a report to the United Nations General Assembly known as "Our Common Future" or the "Brundtland report" to propose long-term environmental strategies for achieving sustainable development by the year 2000 and beyond. This was groundbreaking to the concept of sustainable development, which was the basis for the UN Conference on Environment and Development, the so-called Earth Summit, held in Rio de Janeiro in 1992. The action plan that resulted, known as Agenda 21 (21 refers to the 21st century), was a nonbinding, voluntarily implemented action plan with regard to sustainable development; the greenhouse effect ceased to be a scientific topic and entered full rights in the agendas of governments and economists. At the same time, the United Nations Framework Convention on Climate Change (UNFCCC), as a framework for international cooperation to combat climate change by limiting average global temperature increases, was opened for signature by the 197 Parties that ratified the Convention. The UNFCCC entered into force on March 21, 1994. However, only in 1997 did the UNFCCC become operational with an international agreement, the Kyoto Protocol, which committed its Parties by setting internationally binding emission reduction targets. The detailed rules for the implementation of the Protocol were adopted at the Conference of the Parties (COP 7) in Marrakesh in 2001, and are referred to as the "Marrakesh Accords." Overall, these targets aimed at an average 5% emissions reduction compared to 1990 levels over the 5-year period 2008–12 (the first commitment period) for 37 industrialized countries and the European Union (EU-15). The Kyoto Protocol entered into force at the first Meeting of the Parties to the Kyoto Protocol (CMP 1) and the COP 11 in Montreal on February 16, 2005.

Table 1.1 Overview of global and european legislation on climate and renewable energy

Year	Organization	Conference	Resulting document (main aim)
1979	The first World Climate Conference (WCC)	World Meteorological Organization (WMO), Geneva, Italy	Establishment of the World Climate Programme and the World Climate Research Programme. It also led to the creation of the Intergovernmental Panel on Climate Change (IPCC) by WMO and the United Nations Environment Programme (UNEP)
1987	World Commission on Environment and Development, United Nations General Assembly	Our Common Future	Our Common Future or the Brundtland report: long-term environmental strategies for achieving sustainable development by the year 2000 and beyond
1988	IPCC		IPCC by WMO and UNEP
1990	IPCC	IPCC's first assessment report released	IPCC and second WCC call for a global treaty on climate change. United Nations General Assembly negotiations on a framework convention begin
1991	First meeting of the Intergovernmental Negotiating Committee		
1992	United Nations Conference on Environment and Development	The Earth Summit, Rio de Janeiro, Brazil	Agenda 21: the Rio Declaration on Environment and Development, the Statement of Forest Principles, the United Nations Framework Convention on Climate Change, and the United Nations Convention on Biological Diversity
1994	United Nations Framework Convention on Climate Change (UNFCCC)		Rio Convention: framework for international cooperation to combat climate change
1995	UNFCCC	The first Conference of the Parties (COP 1), Berlin, Germany	
1996	UNFCCC	COP 2, Berlin, Germany	

1997	UNFCCC	COP 3, Kyoto, Japan	Kyoto Protocol (KP): negotiation to set binding emission reduction targets
1998	UNFCCC	COP 4, Buenos Aires, Argentina	The Buenos Aires Plan of Action: strengthen the implementation of the UNFCCC and prepare for the future entry into force of the KP to the Convention, and to maintain political momentum toward these aims
1998	European Commission	98/70/EC— Relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC	Technical specifications on health and environmental grounds for fuels to be used for vehicles (i.e., leaded petrol banned, sulfur in petrol 150 ppm and <350 ppm in diesel, benzene in petrol <1%, aromatics <42%)
1999	UNFCCC	COP 5, Bonn, Germany	Further recalling to demonstrate substantial progress on each of the issues encompassed by the Buenos Aires Plan, in accordance with their respective timeframes
2000	UNFCCC	COP 6, Hague, the Netherlands	Time to decide how to implement the goals agreed by Parties
2001	UNFCCC	COP 7, Marrakesh, Morocco	Capacity building in developing countries; capacity building in countries with economies in transition; development and transfer of technologies
2001	IPCC	IPCC's Third Assessment Report	Bonn Agreements adopted, based on the Buenos Aires Plan of Action of 1998. Marrakesh Accords adopted at COP 7, detailing rules for implementation of KP, setting up new funding and planning instruments for adaptation, and establishing a technology transfer framework
2001	European Commission	2001/77/EC—Directive on Electricity Production From Renewable Energy Sources	European Union targets listed in the White Paper on renewable sources of energy. Regulators aim for a 12% share of gross renewable domestic energy consumption by 2010 and a 20% share by 2020
2002	UNFCCC	COP 8, New Delhi, India	Call for effective action to limit emissions and reduce vulnerability to climate change. Delhi Declaration links climate change to sustainable development

Continued

Table 1.1 Overview of global and european legislation on climate and renewable energy—cont'd

Year	Organization	Conference	Resulting document (main aim)
2003	UNFCCC	COP 9, Milan, Italy	Call for urgent and coordinated action to promote stronger national actions on climate change
2003	European Commission	2003/30/EC—Directive on the Promotion of the use of biofuels and other renewable fuels for transport	National measures for EU member states aiming at replacing 5.75% of all transport fossil fuels (petrol and diesel) with biofuels by 2010
2004	UNFCCC	COP 10, Buenos Aires, Argentina	Progress made since the first Conference 10 years ago and its future challenges, with special emphasis on climate change mitigation and adaptation
2005	UNFCCC	The first Meeting of the Parties to the KP (CMP 1), and COP 11, Montreal, Canada	Entry into force of the KP: Parties launched negotiations on the next phase of the KP
2006	UNFCCC	COP 12, CMP 2, Nairobi, Kenya	Negotiators continued on two processes launched the year before in Montreal to consider the next steps in the international climate effort, and agreed in the final hours to open another track to review the KP. Agreements on approaches to reducing deforestation and accelerating technology transfer. Proposals from South Africa and Brazil on ways to promote stronger action by developing countries
2007	UNFCCC	COP 13, CMP 3, Bali, Indonesia	Bali Road Map: a decision on deforestation and forest management; a decision on technology for developing countries; the establishment of the Adaptation Fund Board; the review of the financial mechanism, going beyond the existing Global Environmental Facility
2007	IPCC	IPCC's Fourth Assessment Report released	Climate science entered into popular consciousness. At the COP 13, Parties agreed on the Bali Road Map toward a post-2012 outcome in two work streams

2008	UNFCCC	COP 14, CMP 4, Poznan, Poland	Commitment from governments to shift into full negotiating mode next year to shape an ambitious and effective international response to climate change, to be agreed in Copenhagen at the end of 2009
2009	UNFCCC	COP 15, CMP 5, Copenhagen, Denmark	Copenhagen Accord: political intent to constrain carbon and respond to climate change, in both the short and long term. Significant advance of negotiations on the infrastructure needed for effective global climate change cooperation, including improvements to the Clean Development Mechanism of the KP
2009	European Commission	2009/28/EC—Renewable Energy Directive	EU member states have to improve their energy efficiency by 20%, the market share of renewable energy sources by 20%, and the share of biofuels in transport fuels by 10% to reduce greenhouse gas (GHG) emissions by at least 20% by 2020
2009	European Commission	2009/30/EC—Amending Directive 98/70/EC	Technical specifications on health and environmental grounds for fuels to be used with positive ignition and compression-ignition engines
		Directive 1999/32/EC and repealing Directive 93/12/EEC	Target for the reduction of life cycle GHG emissions
2010	UNFCCC	COP 16, CMP 6, Cancun, Mexico	Cancun Agreements: key steps forward in capturing plans to reduce GHG emissions and to help developing nations protect themselves from climate impacts and build their own sustainable futures
2011	UNFCCC	COP 17, CMP 7, Durban, South Africa	Road map for implementation: the Durban Platform for Enhanced Action, toward full implementation of the Convention and the KP, the Bali Action Plan, and the Cancun Agreements

Continued

Table 1.1 Overview of global and european legislation on climate and renewable energy—cont'd

Year	Organization	Conference	Resulting document (main aim)
2012	UNFCCC	COP 18, CMP 8, Doha, Qatar	The Doha Amendment to the KP: new commitments for Industrialized Parties for the second commitment period of the KP (from January 1, 2013 to December 31, 2020); a revised list of GHG; amendments to several articles of the KP for the second commitment period
2013	UNFCCC	COP 19, CMP 9, Warsaw, Poland	Key decisions adopted at this conference include decisions on further advancing the Durban Platform, the Green Climate Fund and Long-Term Finance, the Warsaw Framework for REDD Plus, the Warsaw International Mechanism for Loss and Damage, and other decisions
2014	UNFCCC	COP 20, CMP 10, Lima, Peru	Parties adopted the "Lima Call for Action," which elaborated key elements of the forthcoming agreement in Paris
2015	UNFCCC	COP 21, CMP 11, Paris, France	Paris Agreement: limit the temperature increase to 1.5°C above preindustrial levels, promote universal access to sustainable energy in developing countries through the enhanced deployment of renewable energy
2015	European Commission	EU 2015/1513—Amending Directive 98/70/EC and Directive 2009/28/EC	Sustainability measures to reduce GHG emissions, direct and indirect land use change, and to the promotion of advanced biofuels from nonfood feedstock
2016	UNFCCC	COP 22, CMP 12, and first meeting of the Parties to the Paris Agreement (CMA 1), Marrakech, Morocco	The Conference successfully demonstrated to the world that the implementation of the Paris Agreement is under way and the constructive spirit of multilateral cooperation on climate change continues
2017	UNFCCC	COP 23, CMP 13, CMA 1–2, Bonn, Germany	The Climate Change conference will take place on November 6–17, 2017

Adapted from the United Nations Framework Convention on Climate Change—UNFCCC and European Commission.

Several meetings of the COP and CMP followed, and at the end of the first commitment period to the Kyoto Protocol the "Doha Amendment" was adopted (Doha, Qatar, December 8, 2012). The amendment included new commitments for Industrialized Parties for the second commitment period (from January 1, 2013 to December 31, 2020), a revised list of greenhouse gases (GHG), and amendments to several articles of the Kyoto Protocol. In 2015, the COP 21 and the CMP 11 stressed the "urgency of accelerating the implementation of the Convention and its Kyoto Protocol to limit the temperature increase to 1.5°C above pre-industrial levels, to promote universal access to sustainable energy in developing countries through the enhanced deployment of renewable energy." The threshold for entry into force of the "Paris Agreement" was set on October 5, 2016 and the formal agreement was reached on November 4, 2016. Up to now, 144 out of 197 Parties have ratified the Convention (http://unfccc.int/paris_agreement/items/9485.php). In 2018, Parties will take stock of the collective efforts in relation to progress toward the goal set in the Paris Agreement and to inform the preparation of "nationally determined contributions." These are requirements that all Parties have to report regularly on regarding their emissions and their implementation to put forward their best efforts and to strengthen these efforts in the years ahead.

The European Commission (EC) and its member states, strongly support the Kyoto Protocol and further agreements to fight against climate changes. In line with that aim, the EC issued several directives committed to the promotion of the use of energy from renewable sources, to increase energy efficiency, to improve local air quality, and to cut GHG emissions to turn toward a low-carbon economy (e.g., 2001/77/EC and 2003/30/EC).

Afterward, it was acknowledged that given the EU renewable energy targets and the existing agricultural land scarcity in several European regions, land availability for energy crops could lead to a net increase in the cropped area, affecting high-carbon stock lands and resulting in direct or indirect land use change (dLUC and iLUC, respectively). Furthermore, concerns between food and fuel arose, as in the case of the United States, where ambitious ethanol targets (Renewable Fuel Standards) impacted on the availability and prices of corn, mostly on developing countries importing corn and cereals (Wise, 2012).

Thus the EC set a range of ambitious targets to be met by 2020. Energy efficiency would be improved by 20%, the market share of renewable energy sources would be increased to 20%, and the share of biofuels in transport fuels would be raised to 10% to reduce GHG emissions by at least 20% (2009/28/CE). To account for dLUC and iLUC risks, appropriate sustainability requirements of productivity of energy crops grown on already cropped lands were undertaken. To this end a methodology was developed by the EC to account for annualized emissions from carbon stock changes caused by iLUC in terms of CO_2, N_2O, and CH_4, converted into CO_2 equivalent (e.g., $CO_2 = 1$; $N_2O = 296$; $CH_4 = 23$). The methodology addressed, among others, the potential iLUC resulting from biofuels produced from nonfood cellulosic material and from lignocellulosic material. Although in the directive a clear definition of biomass was set (2009/28/CE, art. 2, letter "e"), there was no clear indication of the use of bioenergy crops to minimize iLUC and the aforementioned concerns.

Recently, the EC issued the Directive 2015/1513 to amend the past Directive 98/70/EC on the quality of petrol and diesel fuels (fuel or energy suppliers are required to reduce by at least 6% by 2020 the life cycle of GHG emissions per unit of energy of fuels used in the European Union by road vehicles, nonroad mobile machinery, agricultural and forestry tractors, and recreational craft when not at sea) and Directive 2009/28/EC in regard to the 10% share of biofuels in the transport sector, to sustainability criteria, and to reach, already by 2020, a significantly higher level of consumption of advanced biofuels (biomass feedstock that does not have a high economic value for uses other than biofuels, i.e., lignocellulosic materials).

This is because almost all biofuel production in 2020 is expected to come from crops grown on land that could be used to satisfy food and feed markets by using food/feed crops, the so-called first generation (i.e., oil crops, sugars, and cereals and other starch-rich crops). The promotion of advanced biofuels from nonfood cellulosic material (second generation), including perennial grasses, is expected to play an important role in the decarbonization of transport and the development of low-carbon transport technologies beyond 2020, minimizing the competition with food crops on both dLUC and iLUC. These feedstocks and many others, whose energy content shall be considered to be twice that of the first-generation crops, are listed in Annex IX Part A of 2015/1513. In the group of "perennial or grassy energy crops with a low starch content," species such as ryegrass (*Lolium perenne* L.), switchgrass (*P. virgatum* L.), miscanthus (*Miscanthus* spp.), and giant cane (*A. donax* L.) are listed.

Hence nonfood, lignocellulosic perennial grasses can play a key role as compared with the existing food and feed crops used for biofuel and bioenergy production to reduce competition of food versus fuel, dLUC, and iLUC, and might also contribute to the restoration of severely degraded and heavily contaminated lands (Zegada-Lizarazu et al., 2010).

Perennial grasses belong to the *Poaceae* or *Gramineae* family, the largest form of vascular, herbaceous plants of monocotyledonous type, which include cereals, natural, semipermanent and permanent grasslands, meadows, and bamboos. Broadly, grasses are classified into annual species, which include many cereals, and perennial species, which include many forage and other tall grasses. Grasses are currently the most widespread plants; they have adapted to any conditions of altitude and latitude, from lush rainforests to dry deserts, from warm coastal areas to cold mountains. Grasses are a valuable source of food, feed, and energy for all sorts of wildlife, domesticated animals, and humans (Piperno and Hans-Dieter, 2005).

According to FAO (2005), grasslands are among the largest habitat type in the world; their area is estimated at 52.5 million km^2, or 40.5% of the Earth's landmass. Grasslands are one of the most important biotopes in Europe, ranging from almost desertic types in southeast Spain through steppic and mesic types to humid grasslands/meadows, which dominate in the north and northwest (European Commission, 2008). According to EUROSTAT statistics, grasslands occupied 70.5 million ha within the EU-28 in the year 2013. This area represents 13% and 33% of total land area and total utilized agricultural area, respectively.

Peeters et al. (2014) defined grasslands as "land devoted to the production of forage for harvest by grazing/browsing, cutting, or both, or used for other agricultural purposes such as renewable energy production." The conservation of grasslands is important not only as a feed source but also because they support biodiversity, contribute to the reduction of CO_2 levels from the atmosphere (acting as a carbon sink), and generate several environmental and economic services, such as prevention of fire risk, recreational activities, and tourism (Carrillo et al., 2014). As biomass crops, however, grasslands in the broad sense might need economic support to be comparable to other high-yielding species dedicated to biomass production (Leible et al., 2005). In this context, there is a range of perennial grasses for biomass production that have been tested and selected as most suitable for Europe (Lewandowski et al., 2003; Zegada-Lizarazu et al., 2010; Cosentino et al., 2012).

These species are established only once and harvested yearly in a plantation lifetime spanning from 10 to 25 years. Usually, after harvest, the crop regrows from roots, stools, or rhizomes, resulting in higher energy output to input ratios than annual crops.

According to the EUROSTAT statistics, the total area with energy crops cultivated/harvested in the EU-28 was from 40,620 ha in 2013 to 43,800 ha in 2015. These figures include crops exclusively used for renewable energy production not elsewhere classified and grown on arable land, such as miscanthus (*Miscanthus giganteus* Greef et Deuter), reed canary grass (*P. arundinacea* L.), etc. However, there is no reference to perennial grasses other than miscanthus and reed canary grass, as evidenced by the Latin locution "et cetera" in the energy crops category of the EUROSTAT database. Out of the EU-28 countries, Finland was the leading country in 2013 with 9900 ha, followed by the United Kingdom and Greece (7080 and 6510 ha, respectively). However, while Finland decreased (3500 ha), Greece and Germany increased almost threefold their area in 2015 (15,000 and 8100 ha, respectively). The remaining countries showed slight increases, decreases, or almost constant trends from 2013 to 2015, as shown in Fig. 1.1.

Don et al. (2012) showed that miscanthus is the leading perennial energy grass in Europe, as it is grown from the north Mediterranean to temperate oceanic and central continental areas. Reed canary grass is found at the uppermost European latitudes and northeastern continental zones. Switchgrass (*P. virgatum* L.) is reported in France with only 129 ha.

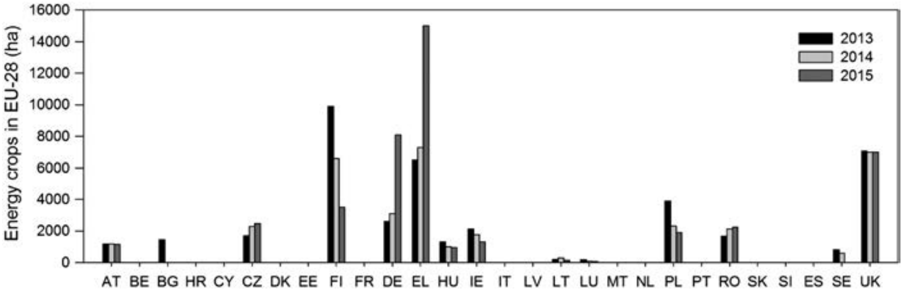

Figure 1.1 Agriculture land used with energy crops (miscanthus, reed canary grass, etc.) in EU-28 from 2013 to 2015.
Adapted from EUROSTAT, 2017. Available at: http://ec.europa.eu/eurostat/web/agriculture/data/database.

It is expected that the new EU directive, research and development in breeding and agronomy will bring into production other perennial grasses (e.g., switchgrass, giant reed, bamboo, etc.) well suited to European environmental conditions.

1.3 Perennial Grasses: An Ideotype of Biomass Crops

The European continent stretches over a large geographic area, ranging from 71°11′N in the north of Norway to 34°48′N in the south of Greece, and from 24°32′W in the west of Iceland to 68°18′E in the Ural Mountains. Hence conditions for plant growth vary considerably across Europe. Metzger et al. (2005) and Jongman et al. (2006) classified the European area into 84 strata, and finally summarized it into 13 major environmental zones. Out of these 13 zones, Cosentino et al. (2012) grouped eight homogeneous climatic zones to grow bioenergy crops. These climatic zones have quite different climatic conditions for agriculture, as reported by the European Biodiversity Observation Network (Wageningen University & Research). The main climatic parameters listed in Table 1.2 (average yearly minimum and maximum air temperatures, rainfall amount and distribution, number of months with temperatures avoiding plant growth, and growing season duration in terms of both days and cumulative growing degree days above a threshold base temperature of 10°C) give an idea of the diverse conditions in Europe.

Generally, the rate of plant growth and development is dependent upon the temperature surrounding the plant, and each species has a specific temperature range represented by a minimum, maximum, and optimum (Hatfield and Prueger, 2015). Air temperature influences all plant growth processes such as photosynthesis, respiration, transpiration, protein synthesis, and translocation, and thus biomass yield (Cosentino et al., 2016). At high temperatures, enzyme activity and the rate of most chemical reactions generally increase, and the translocation of photosynthates is faster so plants tend to mature earlier (Bareja, 2011). At excessively high temperatures, denaturation of enzymes and other proteins occurs, causing heat stress (Mader, 1993). On the other hand, excessively low temperatures can irreversibly damage plant cell walls (Devlin, 1975). Air temperatures above a threshold base temperature (T_b) influence also the number of days throughout a growing season and the cumulative growing degree days (°Cd). This latter temperature determines the beginning and end of the growing season, and it is widely used to derive the physical status of plant development in plant prediction models (Hastings et al., 2009). Number of days of the growing season represents the available timeframe for plant growth in a given environment, which, however, might be constrained by other environmental (e.g., light intensity, light quality, day length, water stress, heat stress, vapor pressure deficit, relative humidity, etc.), physiological (e.g., CO_2 uptake, stomata conductance, transpiration, stomatal limitation to CO_2 uptake, electron transport rate, etc.), and phenological (e.g., onset of flowering, senescence, ripening, etc.) factors affecting plant development.

The amount and distribution of rainfall throughout the growing seasons is among the most important environmental limitations affecting plant growth, development,

Table 1.2 Climatic characteristics of the European environmental zones

Environmental zone	Mean temperature		Rainfall		Months	Active temperature	Growth season
	Min	Max	Oct–Apr	May–Sept	<0°C	>10°C	(Days)
Nemoral	2.4	9.3	309.8	310.8	4.6	2717	196
Continental	4.2	13.1	380.9	393.4	4.1	3294	227
Atlantic North	4.5	11.2	760.7	437.9	1.9	3198	255
Atlantic Central	6.2	13.6	563.5	349.4	0.2	3849	296
Lusitanian	8.4	17.4	851.5	321.7	0.0	4749	353
Pannonian	6.1	15.6	277.7	291.9	2.6	4099	250
Mediterranean North	8.2	18.1	477.8	218.1	0.4	5104	335
Mediterranean South	11.2	21.1	470.1	114.4	0.0	6021	363

Adapted from European Biodiversity Observation Network (EBONE) and Cosentino, S.L., Testa, G., Scordia, D., Alexopoulou, E., 2012. Future yields assessment of bioenergy crops in relation to climate change and technological development in Europe. Italian Journal of Agronomy 7 (e22), 154–166.

and crop yield (Araus et al., 2003; Sánchez et al., 2015). Water participates directly or indirectly in all metabolic processes in living organisms. Excess of water in the soil can injure plants due to lack of oxygen, leading to oxygen stress by hypoxia or anoxia (Bareja, 2011). On the other hand, limited amounts of water during plant growth cause water stress, in turn influencing physiological plant responses, such as photosynthesis mainly related to stomatal closure to restrict water loss by transpiration (Lawlor and Cornic, 2002; Flexas et al., 2007; Cosentino et al., 2016). Furthermore, cell growth, leaf expansion rate, and other plant morphological changes are typical symptoms influenced by water stress (Sánchez et al., 2015; Cosentino et al., 2016).

Typically, perennial grasses are warm season, C_3 (e.g., *A. donax*, *P. arundinacea*, *Phyllostachys* spp.) or C_4 (*Miscanthus* spp., *P. virgatum*), photosynthetic pathway plants; however, they show quite different requirements with regards to rainfall, temperature trends, and cumulative growing degree days (Lewandowski et al., 2003).

Basically, from north to south of Europe, average minimum and maximum yearly air temperatures and thus cumulative growing degree days increase, while the number of months with temperatures lower than 0°C and rainfall amount decreases. Rainfall distribution throughout the growing season turns from very regular under northern–central to uneven under southern environments.

In northern and continental climates (e.g., Nemoral, Continental, and Pannonian), spring frost might delay emergence of perennial grasses and growth might be cut short by fall frost, impacting on growing degree days accumulation, and thus on biomass yield. In oceanic temperate climates (e.g., Atlantic North and Central), where summer conditions remain relatively cool with low light intensity, a plant must capitalize on the long spring–summer day lengths to achieve high biomass yield. Lusitanian and Mediterranean North show very favorable climatic conditions during the spring–summer period, high light intensity allowing high degree days accumulation, and thus plant growth and yield. However, summer water deficit and heat waves usually affect growth to a different extent in Mediterranean North. Mediterranean South has very favorable climatic conditions from spring to fall, as evidenced by the highest growing degree days overall. However, severe water stress, which usually lasts from 2 to 6 months (Ne'eman and Goubitz, 2000), and short dry periods from fall to spring limit plant growth and biomass yield to a greater extent (Cosentino et al., 2007a; Gulías et al., 2009). Furthermore, high summer temperatures can shorten the growing season, although plants might benefit from the warm fall conditions to keep on growing (Scordia et al., 2014).

Thus perennial grasses might take advantages and constraints from the diverse climatic characteristics of European environmental zones where they are supposed to be grown.

As with any other plant, there is no one perennial grass that fits all climatic conditions (Mitchell et al., 2016). Hence plant response to environmental limitations during the growing season dictates the selection of the crop tailored to the different environmental zones. Furthermore, other factors, such as soil type, slope, or other terrain limitations, might either limit or foster the right plant choice (Cosentino et al., 2012). Despite the environmental conditions where perennial grasses are grown, the ideotype (ideal crop type) of biomass crop should have the following traits, as summarized by Cosentino et al. (2007b):

- High biomass yield, as close as possible to the potential yield in a given environmental zone;
- Stable biomass yield under changing climatic conditions and stand age;
- High resource use efficiency (radiation, nutrient, and water);
- Pest resistance;
- High competitiveness to weeds from the establishment year;
- Resistance to abiotic stresses (dryness, high or low temperatures, excess of soil moisture or under soil deficit conditions);
- Ability to thrive under unfavorable biophysical conditions (e.g., unfavorable soil texture, shallow depth, saline, contaminated soils, steep slopes);
- Low-cost establishment (e.g., by seeds) and low external input (e.g., soil tillage, fertilization, irrigation, weed and pest control, harvest) requirements;
- Responsiveness to existing farm equipment;
- Stable biomass quality for specific end uses.

Table 1.3 shows research findings on the main traits of giant reed, miscanthus (i.e., *Miscanthus* × *giganteus*), switchgrass, bamboo, and reed canary grass as ideotypes of bioenergy crops.

According to the climatic requirements, reed canary is most suited to the northern environmental zones of Europe as it shows frost tolerance traits and also good winter hardiness (Lewandowski et al., 2003).

Switchgrass and miscanthus have a wider range of climatic adaptability and are best fitted to central and southern Europe. However, dry summer periods are a fundamental problem for these crops (Zegada-Lizarazu et al., 2010; Cosentino et al., 2007a). Giant reed is a drought-resistant crop well adapted to warm temperate and semiarid environments with high temperatures and long summer dryness (Cosentino et al., 2014, 2016). Although bamboos are not naturally widespread in Europe, there is evidence of its growth in Western Europe (El Bassam, 1998; Potters et al., 2013). Yields of more than 30 t DM ha^{-1} have been measured for giant reed, miscanthus, and switchgrass in optimal growing conditions, while yields of up to 12 t DM ha^{-1} for reed canary grass have been measured (Lewandowski et al., 2003; Cosentino et al., 2006, 2007a).

Perennial grasses are high resource use efficient crops in terms of radiation, water, and nutrients; they are also low-input demanding (Kiniry et al., 1999; Cosentino et al., 2007a, 2014, 2016; Ceotto et al., 2013; Triana et al., 2014). In general, perennial grasses have few natural enemies (Lewandowski et al., 2003; Zegada-Lizarazu et al., 2010); however, a dramatic drawback is the low weed competition at the establishment year (Scordia et al., 2015). Therefore during this period, proper control of weeds, limited fertilization (mainly N), and if necessary supplemental irrigation are usually recommended (Parrish and Fike, 2005).

Perennial grasses have the ability to thrive under dry, hot prone environments (Cosentino et al., 2016), on poorly drained and flooded soils (Lewandowski et al., 2003; Mann et al., 2013), under soil salinity (Sánchez et al., 2015; Anderson et al., 2015; Stavridou et al., 2016), on heavily contaminated soil (Barbosa et al., 2015), and on steep slopes (Cosentino et al., 2015a).

Table 1.3 Main trait of giant reed (GR), miscanthus (MS), switchgrass (SW), bamboo (BA), and reed canary grass (RCG) as ideotypes of perennial grass

Crop	Yield	RUE	NUE	WUE	PR	WC	D	LT	HT	ESW	SWD	SD	SA	CON	SS	CE	IR	FE	BQ	GV
GR	H	MH	MH	H	H	L	MH	L	H	H	MH	ML	H	MH	MH	H	L	L	M	L
MS	H	MH	MH	MH	H	L	ML	MH	M	MH	ML	M	MH	MH	M	MH	ML	M	M	M
SW	MH	MH	MH	H	H	L	M	M	MH	M	M	MH	MH	–	M	L	ML	MH	M	MH
BA	M	–	–	–	H	L	–	–	–	–	–	–	–	–	–	H	–	–	M	L
RCG	ML	–	–	–	H	L	M	H	M	H	ML	–	–	–	–	L	ML	MH	M	MH

BQ, Biomass quality for specific end uses; *CE*, cost establishment; *CON*, contaminated soils; *D*, dryness; *ESW*, excess soil moisture; *FE*, amenable to existing farm equipment; *GV*, genetic variability; *H*, high; *HT*, high temperatures; *IR*, input requirement; *L*, low; *LT*, low temperatures; *M*, medium; *MH*, medium-high; *ML*, medium-low; *NUE*, nutrient use efficiency; *PL*, fitting in existing postharvest logistic; *PR*, pest resistant; *RUE*, radiation use efficiency; *SA*, saline soil; *SD*, shallow depth; *SS*, steep slopes; *SWD,* soil water deficit; *WC*, weed competitive at establishment; *WUE*, water use efficiency.

However, most of them are still at the very first stage of breeding programs, as they are found in wild form, although a certain genetic variability exists. Some perennial grasses are unable to produce viable seeds, limiting breeding to a greater extent. This is the case of giant reed (*A. donax* L.), the triploid hybrid *Miscanthus* × *giganteus*, or bamboo (*Phyllostachys* spp.), resulting in restricted genetic diversity. On the other hand, switchgrass (*P. virgantum* L.) and reed canary grass (*P. arundinacea* L.) produce viable seeds; however, their establishment often fails because of the small seed size and morphology, seed dormancy, and low early seedling vigor (Lewandowski et al., 2003; Zegada-Lizarazu et al., 2012, 2013; Berti and Johnson, 2013). Therefore future development needs to focus on reliable and low-cost establishment, and also on seeds. Seeds obtained by breeding programs might allow the development of optimized perennial grass varieties (ideotypes) adapted to different European conditions. Proper varieties and the optimization of agronomic practices will allow their potential yield to be reached in a given environmental condition.

Researchers should never cease to explore new genetic resources from the wild germplasm. In this regard, Cosentino et al. (2015b) showed as a species native from northern coast of Africa, *Saccharum spontaneum* L. spp. *aegyptiacum* (Willd.) Hackel, was well adapted to the drought environment of southern Europe. This species encloses a wide range of agronomically desirable traits of biomass crop, such as C4 plant, high biomass yield, active assimilation rates during drought–stress periods, ability to use water efficiently, and satisfactory biomass quality.

On the island of Sardinia, Sulas et al. (2015) performed a comparison of several native Mediterranean populations of *Piptatherum miliaceum* (L.) Coss, evidencing interesting traits for bioenergy production with favorable combinations of biomass yield and lignocellulosic contents.

1.4 Perennial Grasses in a Biobased Economy

Perennial grasses are herbaceous, lignocellulosic plants. Their chemical composition is made up primarily from structural polysaccharides, namely, cellulose and hemicelluloses, and by lignin (Scordia et al., 2014). In addition, small fractions of nonstructural components, such as extractives, protein, lipids, pectin, and ash, build up the lignocellulosic biomass (Wyman, 1994).

Lignocellulosic biomass is the most abundant and lowest-cost raw material on Earth, tailored to develop a competitive, resource efficient, and low-carbon economy in Europe.

Scarlat et al. (2015) summarized the main EU policies toward the modern bioeconomy, including “A Roadmap for Moving to a Competitive Low Carbon Economy in 2050” (EC, 2011a), the Europe 2020 flagship initiatives, namely, “An industrial policy for the globalization era” (EC, 2010) and “Resource efficient Europe” (EC, 2011b), and the green economy concept (UNEP, 2014). In this latter, the bioeconomy is centered on the use of renewable raw materials and the application of research, development, and biotechnology innovation in several productive sectors, such as food, feed, paper and pulp, and biofuels. In comparison to the environmental emphasis of the green economy, the bioeconomy focus is on new growth opportunities in both traditional and emerging biobased sectors while considering global challenges (e.g., raw material supply in security), resource, and environmental constraints (IEEP, 2014; EC, 2014).

Bioeconomy is steadily increasing, with a current estimate of the overall market (including agriculture, food and beverage, agroindustrial products, fisheries and aquaculture, forestry, wood-based industry, biochemicals, enzymes, biopharmaceuticals, biofuels and bioenergy) of about €2.4 billion, using about 2 billion tons and employing 22 million persons in the European Union (Scarlat et al., 2015).

As new sectors are emerging, the transition toward the bioeconomy will mostly rely on the availability of sustainable biomass in terms of yield per unit land area, competition for lands, food, and resources, and biotechnology developments. In this context, lignocellulosic perennial grasses might be the leading crops to supply biomass raw material. On the other hand, biotechnology is constantly exploring new routes for conversion of lignocellulose to biofuels and other added-value products (organic acids, pharmaceuticals, commodity chemicals, and food/feed).

Modern biobased industries are adopting a cascading approach to biomass uses, prioritizing its use for socially preferable products over its use for energy (Keegan et al., 2013). Fig. 1.2 shows that such a mechanism would be an opportunity to maximize the efficiency and add values to the biomass raw material. Maximum priority is given to extract the highest added-value products, and then downward to those with lower added value in a cascade approach. Hence biopharmaceuticals and fine chemicals should undergo the first extraction followed by nutritional supplements, biopolymers, bioplastics, bulk chemicals, fertilizers and detergents, biomaterials (fiber for papermaking, building material, phonic insulating material, mulching and

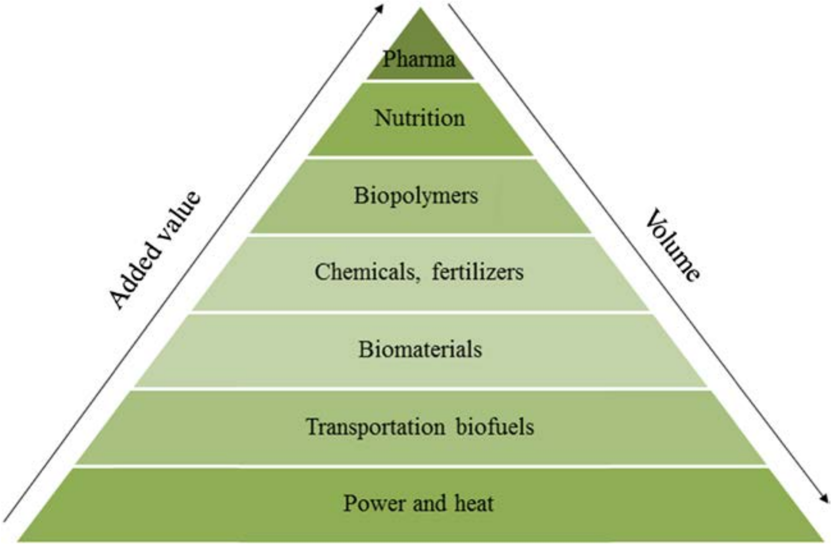

Figure 1.2 Cascading approach of lignocellulosic biomass in the bioeconomy concept.

biodegradable products for gardening and animal bedding, etc.), transportation biofuels (bioethanol, biodiesel, biomethane), and finally power and heat from the residual biomass. Of course, depending on the biomass type (e.g., oil, sugar, starch, lignocellulosic), high-value molecules will have a lower volume as compared to the whole biomass if used to generate power and heat.

The contribution of biotechnology in multiple areas will be crucial to close the loop and will give increasing opportunities for biomass use (Scarlat et al., 2015).

Nowadays, lignocellulosic perennial grasses are mainly converted via thermochemical or biochemical conversion pathways to produce heat, energy, liquid and gaseous biofuels, intermediates carriers, and by-products. In nonenergy applications, physical, chemical, or biological processes can be applied (Fig. 1.3).

Hence current processes are at the medium-lower range of the cascade pyramid approach, although many upward examples are widely studied worldwide. Ideally, biomass should undergo a complete fractionation into the three major components, namely, hemicellulose, cellulose, and lignin, for maximum possible utilization.

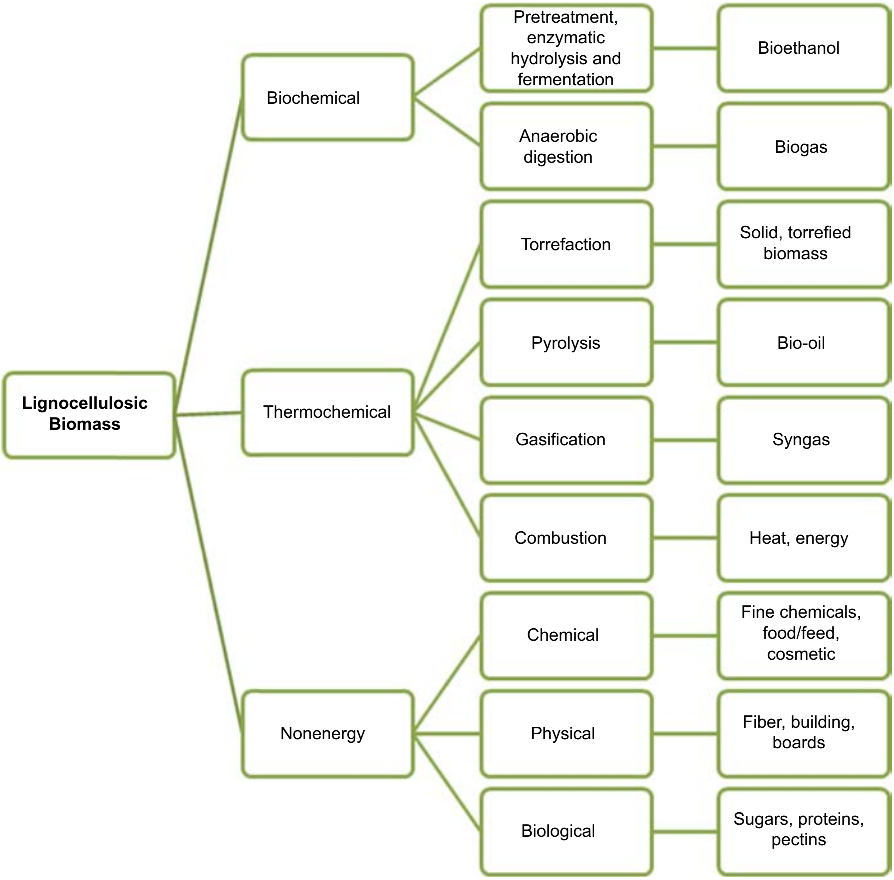

Figure 1.3 Energy and nonenergy applications of perennial grasses.

From the hydrolysis of hemicelluloses, both pentose and hexose sugars can be recovered to produce biofuels (bioethanol), sweetener (xylitol) and furan derivatives (furfural), plant gum, and weak acid (acetic acid) from acetyl groups in hemicelluloses. From cellulose hydrolysis and glucose recovery, biofuels (bioethanol), furan derivatives (hydroxymethyl furfural), organic acids (formic and levulinic acid), solvents, lubricants, chemicals, and polymers can be obtained. Phenolic compounds, natural binders, adhesives, sulfur-free solid fuels, and subbituminous coal might come from lignin.

Thus a huge number of green products can enter several industrial commodities (pharmaceuticals, food, feed and beverages, chemicals, etc.), increasing the lignocellulosic conversion revenues per ton of dry raw material (Kamm et al., 2008).

1.5 Sustainability of Perennial Grasses

Perennial grasses are expected to play an important role in cutting CO_2 emissions, in contributing to the maintenance of energy supplies, and in providing benefits in terms of soil structure and stability (e.g., reduced soil loss, erosion, and runoff), soil quality (e.g., increase in soil fertility, organic matter, and nutrient retention), and biodiversity (e.g., cover for native wildlife) (Lewandowski et al., 2003).

Socioeconomic benefits are expected from the development of new markets to promote regional economic structures, to provide alternative sources of employment in rural areas, and to promote the use of surplus and marginal lands. Therefore, in the long term, the successful implementation of energy crop systems should seek to ensure income generation, environmental sustainability, energy security, flexibility, and replicability (Soldatos et al., 2010). A summary of environmental and socioeconomic benefits offered by perennial grasses as bioenergy crops is shown in Table 1.4.

Several studies have addressed the sustainability of perennial grasses; however, the conversion of a fossil fuel-based economy into a biobased economy will probably be constrained by the overall limited availability of biomass in the European Union, which remains one of the major sustainability challenges (Scarlat et al., 2015).

Sustainable agricultural intensification has been defined as “producing more output from the same area of land while reducing the negative environmental impacts and at the same time increasing contributions to natural capital and the flow of environmental services” (Pretty et al., 2011).

Thus the need to raise biomass availability when land is limited (e.g., European Union) might lead to unsustainable use of water, fertilizers, and pesticides with additional problems linked to pollution and water scarcity (Alexopoulou et al., 2015). An integrated management strategy aimed at ensuring sustainable biomass production and sustainable use of natural resources must be prioritized.

The life cycle assessment of miscanthus (*Miscanthus* × *giganteus*), giant reed (*A. donax* L.), and switchgrass (*P. virgatum* L.) on marginal lands in the Mediterranean region showed that the cultivation of perennial grasses and their use for stationary heat and power generation can achieve substantial GHG emissions and nonrenewable

Table 1.4 Main environmental and socioeconomic benefits of perennial grasses

Environmental benefits	Socioeconomic benefits
• Less water consumption; • Low fertilizers and pesticides requirements; • Low greenhouse gas emissions; • Phytoremediation capacity; • Reduction of soil degradation and erosion; • Adaptability to marginal lands; • Permanent soil cover; • Natural habits for wildlife	• Development of new markets (e.g., biofuels and green products); • New sources of income and employment in rural areas; • Development of regional economic structures; • Biodiversity increase; • Potential inland renewable energy sources (>energy security); • Improve the education, training, and assistance services provided for farmers

Modified from Sims, R.E.H., Hastings, A., Schlamadinger, B., Taylor, G., Smith, P., 2006. Energy crops: current status and future prospects. Global Change Biology 12, 2054–2076; Zegada-Lizarazu, W., Elbersen, W., Cosentino, S.L., Zatta, A., Alexopoulou, E., Monti, A., 2010. Agronomic aspects of future energy crops in Europe. Biofuels, Bioproducts Biorefinery 4 (6), 674–691.

energy savings up to 13 t CO_2 eq ha^{-1} yr^{-1} and 230 GJ ha^{-1} yr^{-1}, respectively (Schmidt et al., 2015). The authors concluded that the cultivation of perennial grasses on marginal land in the Mediterranean region provides potential for climate change mitigation together with other comparatively low environmental impacts.

Life cycle energy use and GHG emissions savings of reed canary grass, miscanthus, giant reed, and switchgrass used in combined heat and power generation have been ascribed as one of the most efficient options in terms of land use, provided that the biomass is cultivated on surplus agricultural land to avoid iLUC (Rettenmaier et al., 2010).

The environmental impact assessment of perennial grasses on marginal Mediterranean lands showed that the biogenic system, which included cultivation, harvest and biomass pretreatment, conditioning and logistics, conversion, use, and end of life, had low erodibility potential, reduced disturbance of soil properties, and minimal hydrological impacts, with few environmental side effects (Fernando et al., 2015).

Several reports dealing with energy balance concluded with the outstanding performances of perennial grasses. Amaducci et al. (2017) showed that net energy gain (NEG) and energy return on investment (EROI) were much higher for perennial grasses than for woody crops.

Monti et al. (2009) reported a mean annual NEG of 200 GJ ha^{-1} yr^{-1} for switchgrass fertilized with 200 kg N ha^{-1} yr^{-1} in the north of Italy.

Mantineo et al. (2009) showed either low or negative net energy yield at the establishment year in giant reed and miscanthus grown in the south of Italy under nitrogen fertilization and irrigation treatments, due mainly to the concurrent low biomass yield and high energy costs required to establish perennial grasses. However, in the second and third year, net energy yield of giant reed was exceptionally high (487.2 and

611.5 GJ ha^{-1}, respectively), while miscanthus attained its highest net energy yield at the fourth cultivation year (447.2 GJ ha^{-1}).

Soil erosion is a crucial issue for European soils. As reported by Panagos et al. (2015), the mean soil loss rate is around 2.46 t ha^{-1} yr^{-1}, resulting in a total soil loss of 970 Mt year^{-1}. Soil erosion has become part of the environmental agenda in the European Union, with special attention paid to the 4 Mha of croplands that currently have unsustainable soil loss rates of more than 5 t ha^{-1} yr^{-1}.

The key role of perennial grasses in terms of soil erosion mitigation has been well documented (Wuest et al., 2006; Cosentino et al., 2008; Feng et al., 2011).

Cosentino et al. (2015a) showed that *Miscanthus* × *giganteus* contained soil losses of 0.09 t ha^{-1} as compared with 4.81 t ha^{-1} of Italian ryegrass and 28.2 t ha^{-1} of durum wheat in a Mediterranean area with 26%–28% slope during one growing season. Similar trends were observed when giant reed was compared with annual crops sown in fall and fallow plots (soil losses of 1.27, 5.0, and 4.34 t ha^{-1}, respectively). In the last experimental year, giant reed kept minimal soil losses (0.07 t ha^{-1}), while durum wheat reached 10.1 t ha^{-1}.

In addition to soil erosion mitigation, perennial grasses also allowed CO_2 to be stored in the soil due to a very high level of plant residues left from both above- and belowground biomass, as well as from untilled soil for a long period (>10 years). It was estimated that 6.99 t CO_2 ha^{-1} can be stored with a well-established stand of miscanthus, and up to 9.44 t CO_2 ha^{-1} with a well-established giant reed.

Carbon storage potential of switchgrass grown on marginal lands, or marginal lands plus 5% of the less productive cereal lands in the Mediterranean region, was estimated by the DAYCENT model. It was shown that potential emission savings from switchgrass cultivation can be highly relevant, from 0.02 to 0.62 t ha^{-1} of annual soil organic carbon accumulation, due to restoration of degraded lands, reduced soil tillage, perennial soil cover, high level of field residues, low N management, and fossil fuel displacement. These environmental benefits could also be an income opportunity for farmers once sequestration of atmospheric carbon is rewarded as “environmental credits” (Nocentini et al., 2015).

Monti and Zegada-Lizarazu (2016) evaluated the effects of different nitrogen fertilization levels on biomass production and soil organic carbon accumulation of giant reed over 16 years. Mean total soil organic carbon stock gains were 1.0 and 0.6 t C ha^{-1} yr^{-1} in the N160 (160 kg N ha^{-1} yr^{-1}) and N0 treatments (unfertilized), respectively, recommending that giant reed be grown without the burdens of fertilization despite the apparent benefits on soil organic carbon and marginal yield increments of fertilized plots.

It is widely accepted that the establishment of a monoculture will have negative effects as compared to a natural system (Mattsson et al., 2000), and the farther the system shifts from the native conditions, the more severe will be the impact on biodiversity (Paine et al., 1996). Biodiversity impact assessment is highly site specific once it analyzes the drivers of change and how these drivers affect the structure of ecological units and existing populations (Biewinga and van der Bijl, 1996; Rodrigues et al., 2003; Slootweg and Kolhoff, 2003). By definition, any natural vegetation type has the best performance concerning the ecosystem services and consequently biodiversity (Smeets et al., 2009).

Fernando et al. (2015) compared the biodiversity impact of perennial grass systems to a natural forest in Europe and annual cropping systems, attributing the maximum score to a climax forest. Because of minimal soil disturbance compared to annual crops, perennial grasses have a high cover value for wildlife (Borjesson, 1999; Boehmel et al., 2008; Prochnow et al., 2009; Werling et al., 2014), scoring between forests and annual crops in terms of effects on biodiversity. Dense aboveground and high belowground biomass favors diversity and occurrence of soil fauna and soil microorganisms, respectively (Borjesson, 1999), and provides shelter for invertebrates, birds, and small mammals (Smeets et al., 2009; Bellamy et al., 2009; Semere and Slater, 2007a,b). Higher biodiversity value was given to miscanthus as compared with switchgrass plantations due to lower yields of the latter. Although giant reed behaved similarly to miscanthus, its invasive behavior penalized this crop, as native vegetation might be quickly replaced.

Other alternative uses and direct economic advantages might be provided by perennial grasses, as, for example, in the greening measures of the Common Agricultural Policy and in the sustainable provision of environmental services, such as flood risk reduction, soil protection, nitrate leaching mitigation, land restoration, use of marginal lands and less favored areas, controlling nonpoint source pollution, and mitigating climate changes.

1.6 Research Perspectives

Although there exists a near-unanimous scientific consensus on the overall environmental sustainability of perennial grasses, knowledge of many research tasks must still be raised. Increasing interest in the use of perennial grasses as biomass crops in Europe has been supported by several European projects starting from the early 1990s (i.e., Miscanthus productivity networks, Giant reed network, Switchgrass for Energy, Bioenergy Chains, 4FCROPS, EUROBIOREF, OPTIMA, OPTIMISC, GrassMargins, among others); however, research projects usually lack long-term financial support, with only establishment and a few years' growth period being covered. This is a dramatic drawback since perennial grasses are established only once and after yearly harvest the crop regrows from roots, stools, or underground stems (rhizomes) over a 10–25-year lifespan against 2–4-year research projects. For example, Fig. 1.4 shows the beginning and end of two European research projects dealing with *Miscanthus*×*giganteus* (Miscanthus productivity network, AIR CT920294) and *A. donax* (Giant reed productivity network, FAIR CT962028) at the University of Catania (Italy). Ten years of no financing followed (from 2001 to 2011); however, both stands were managed with internal funds with the aim of having a clear picture of the long-term behavior of these crops in rain-fed conditions in the south Mediterranean area. New lymph came from the OPTIMA project (FP7 289642, from 2011 to 2015); however, from 2015 both stands were being managed again with internal funds.

It is clear that without foresight, land and internal fund availability both crops would have been removed after 4 years of growth, to be reestablished when financial support would be available again.

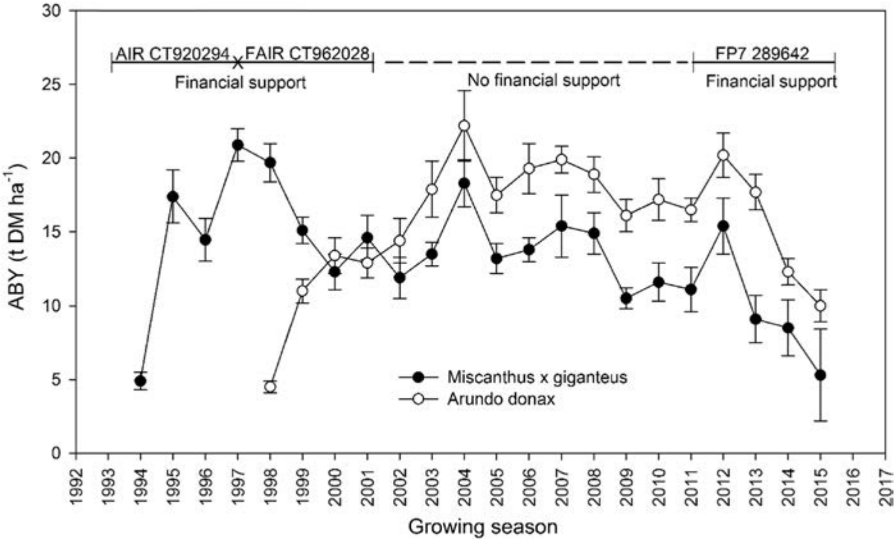

Figure 1.4 Public financial support for field research activities on *Miscanthus × giganteus* (Miscanthus productivity network, AIR CT920294), *Arundo donax* (Giant reed productivity network, FAIR CT962028), and both species (OPTIMA, FP7 289642) at the experimental fields of the University of Catania, Italy.

Modified from Alexopoulou, E., Zanetti, F., Scordia, D., Zegada-Lizarazu, W., Christou, M., Testa, G., Cosentino, S.L., Monti, A., 2015. Long-term yields of switchgrass, giant reed, and miscanthus in the Mediterranean basin. Bioenergy Research 8, 1492–1499.

Thus long-term yield studies, particularly in large fields, are challenging and difficult to maintain due to the limited duration of research projects, discontinuity of funding, and changing research objectives. At the same time, comprehensive real yield data over a plant's lifespan would be necessary for providing more reliable information to farmers and entrepreneurs with consistent and affordable economic plans, such as adequate plantation size and tailor-designed processing plants (Alexopoulou et al., 2015). Limited information on long-term productivity of perennial grasses has been partly fulfilled by prediction models (Kiniry et al., 2008; Davis et al., 2010; Chamberlain et al., 2011; Miguez et al., 2012). These models, however, are often based on a few short-term studies, variable assumptions, different species, genotypes, environments, and biomass end uses (Wullschleger et al., 2010). Thus the uncertainty/risk of result exploitations could sometimes be unacceptable, since significant changes on stand lifespan could heavily condition final profitability of the plantation. Long-term data across different environments will help to prevent such uncertainty, while providing farmers and entrepreneurs with sound information to estimate reliable and affordable strategies on what, where, and how long to grow perennial grasses (Alexopoulou et al., 2015).

The sustainable development of bioenergy chains based on perennial grasses needs to rely on low-input agronomic practices optimization and tailored varieties for different environmental conditions.

Most perennial grasses are undomesticated crops, collected from wild environments and tested in field trials, hence they are still at the first stage of breeding programs. Some of them are unable to produce viable seeds, limiting breeding to a greater extent. This is the case of giant reed (*A. donax* L.), the triploid hybrid *Miscanthus* × *giganteus*, and bamboo (*Phyllostachys* spp.), resulting in restricted genetic diversity. On the other hand, switchgrass (*P. virgantum* L.) and reed canary grass (*P. arundinacea* L.) produce viable seeds; however, their establishment often fails because of the small seed size and morphology, seed dormancy, and low early seedling vigor (Lewandowski et al., 2003; Zegada-Lizarazu et al., 2012, 2013; Berti and Johnson, 2013). Thus the response of different ecotypes to seedbed preparation methods (no tillage, minimum tillage, and conventional tillage), sowing time, seedling density, and weed control should be deeply investigated. New techniques have been attempted for seed-sown crops: the hydroseeding of switchgrass although underperforming conventional seeding under certain circumstances might result in a valuable alternative for particular conditions, especially for sloping areas where soil tillage and conventional sowing are difficult to perform (Scordia et al., 2015). However, further investigations still need to be done to optimize this technique for switchgrass and/or for reed canary grass (i.e., specifically, optimized mulch for these species, identification of the best sowing time, etc.).

On the other hand, the most effective method to propagate giant reed and miscanthus appears to be the use of rhizomes with transplanting between the end of winter and the middle of spring (Copani et al., 2013). However, rhizome cuttings are economically and environmentally expensive because of low mechanization and the associated environmental impact to dig up, break apart, and replant rhizomes. It has been shown that propagation via stem cuttings of miscanthus and giant reed represents a more economical and environmentally friendly method than rhizome propagation (Boersma and Heaton, 2012; Scordia et al., 2015). This method does not require the considerable work involved in rhizome cutting preparation, as the propagation material is the aboveground biomass; it also makes the multiplication rate several orders of magnitude greater than rhizome propagation (Boersma and Heaton, 2012). However, a question remains on the effect of transplanting time when direct-field stem transplanting is performed (Scordia et al., 2015). Indeed, temperature seems to play a critical role when water does not represent a limiting factor. Optimization of factors such as air temperature (i.e., transplanting time), node position (apical, median, and basal part), and stem node pretreatment (i.e., hydration, growth regulators, etc.) might strongly enhance rooting rate. When this propagation technique is optimized, it might be the time to consider it as an alternative and feasible technique to increase propagule ratios, decrease establishment costs, and decrease environmental impacts, fitting also the nursery activity (Scordia et al., 2015).

As previously mentioned, breeding programs are still in their infancy for most perennial grasses. The initial objective was to improve biomass yield and quality (Clifton-Brown et al., 2008); current objectives attempt to deliver plants suited to a range of growing conditions and tolerant to abiotic stresses that characterize marginal lands.

The breeding chain can be split into five steps, starting with the collection and characterization of wild germplasm and ending with the upscaling of commercially relevant hybrids, which meet the needs of industrial end users (private communication,

I. Lewandowski, J. Clifton-Brown, and D. Murphy-Bokern). The most advanced breeding efforts in Europe are currently reported for miscanthus. Researchers at Aberystwyth University (Aberystwyth, UK), Julius Kühn-Institut (Braunschweig, Germany), and partners from China, Japan, South Korea, and Taiwan, together with CERES Inc. (a US crop biotechnology company), began the development of seed-based hybrids by germplasm collection of key species (i.e., *Miscanthus sinensis*, *Miscanthus sacchariflorus*, and *Miscanthus floridulus*) in Asia to increase the genetic diversity available for breeding (Clifton-Brown et al., 2017). As a result, breeding in miscanthus is close to field testing of novel hybrids (private communication, J. Clifton-Brown).

Breeding programs have been established in the United Kingdom for reed canary grass (O'Donovan et al., 2015), while most activities are in the germplasm collection and characterization for giant reed, although genetic and metabolic exploration through transcriptome analysis has been reported (Sablok et al., 2014).

The release of new varieties tailored to specific locations would be accelerated by means of prediction models to assess the yield performance of diverse genotypes in a range of climatic regions and thus expand the European market though new elite varieties (Clifton-Brown et al., 2008). However, plant phenology of these new elite varieties should be carefully assessed in variegate environments, thus multisite trials become necessary for a deep understanding of genotype × environment interactions.

The successful introduction of perennial grasses into existing cropping systems needs to focus on reliable and low-cost establishment, and also on seeds and high seedling competition to weeds at the establishment year. Due to low plant density at establishment (10,000–20,000 plant ha^{-1}) and the tradeoff of sink- and source-limited growth (Luquet et al., 2006), perennial grasses usually invest most of the carbohydrate pool to build up belowground (root and rhizomes) rather than aboveground biomass, which translates into low biomass yield and low weed competition at the establishment year. This might be severely exacerbated when growing perennial grasses in poor and harsh environments.

Physiological studies on specific targeted traits would allow the identification of traits associated with early emergence for better crop establishment (e.g., relative growth rate), osmotic regulation, photosynthesis, and transpiration efficiency to screen genotypes with improved performance under stresses to develop appropriate breeding programs. Furthermore, the identification of senescence and regulation of metabolite degradation traits might help to identify the cell death process and thereafter decide on ways to induce or delay cell death in senescing leaves directly impacting on the capacity for rapid drying, therefore improving yield and quality.

Biotechnology through genomic studies and development of large-scale molecular markers will provide important information and efficient molecular tools for breeding of plants tolerant to abiotic stresses.

In addition to propagation and weed control, agronomic management of perennial grasses is well behind as compared to the well-known conventional crops. Appropriate agricultural practices for crop establishment, growth, development, and harvest would allow farmers to diversify their activities, without incurring costly and risky operations. A package of low-input techniques must be optimized to target perennial grasses, particularly in marginal lands, by taking into account the interaction between soil, plant, atmosphere, and optimal use of resources to achieve the highest output with minimal (on-farm and/or off-farm) input supply. Proper energy balances might allow the optimization of both production systems and efficient use of resources.

Agronomic practices, such as soil management, water, fertilizers, and agrochemicals management, intercropping and ways to reduce biomass losses during harvesting and storage, and organization of crop logistics for the various end uses and systems with proven and validated technologies that would not require significant modification to those currently being used by farmers, will help to introduce perennial grasses at the farm level.

There is also a need to develop programs for supporting small-scale but higher value applications of perennial grasses to develop attractive market options. This should also include options of “on-farm biorefineries” that help to keep a higher proportion of the value generated from biomass and its processing and use the remainder on the farm. The development of on-farm biorefinery concepts that allow decentralized biomass densification and valorization can help to involve farmers in local biobased value chains. Farmers will only be willing to do this if biomass markets are reliable or if long-term contracts are granted. Therefore the development of biomass marketing structures should be supported.

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Miscanthus

2

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Miscanthus is a perennial rhizomatous grass native to East Asia. Field experiments have confirmed its outstanding low-temperature C_4 photosynthesis resulting in a high biomass yield potential with low input requirements (Lewandowski et al., 2000; Davey et al., 2017). It was first introduced into Europe from Japan in the 1930s by the Danish plant collector Axel Olsen. Today, miscanthus is a leading perennial energy grass in Europe due to its high dry matter yield potential and its ability to grow under a wide range of climatic conditions from southern to northern Europe (Clifton-Brown et al., 2017). The high proportion of holocellulose (cellulose + hemicellulose) in its cell walls makes it a multipurpose feedstock for conversion into a wide range of materials and uses in a number of energy production systems. Currently, diverse and promising hybrids are being evaluated in different climates and soils, including marginal lands less suitable for food production, with the aim of supplying biomass quality suited to various end uses.

The geographic distribution of miscanthus genotypes in its area of origin, East Asia, indicates that *Miscanthus sinensis* and *Miscanthus sacchariflorus* have the potential to grow under diverse climatic conditions, whereas *Miscanthus floridulus* is limited to latitudes below 30°N (Fig. 2.1). The natural hybrid *Miscanthus* × *giganteus* is thought to have developed from *M. sinensis* and *M. sacchariflorus* (Stewart et al., 2009). Although this natural hybridization has occurred multiple times (Matumura et al., 1985), today almost all commercial miscanthus production is based on the single genotype accession collected in Japan in 1935.

2.1 Miscanthus Taxonomy

Miscanthus belongs to the same grass tribe as maize, sorghum, and sugarcane: the Andropogoneae. Its morphological and molecular characterization indicates that it is closely related to sugarcane and sorghum (Hodkinson et al., 2002). Studies report varying numbers of species for the genus *Miscanthus*, ranging from 14 to 23 (Lee, 1964a,b; Clayton and Renvoize, 1986). A taxonomic scheme is presented here that was developed by Steve Renvoize of the Royal Botanic Gardens Kew and published in a review (Clifton-Brown et al., 2010). It has five sections (Fig. 2.2), all of which are found in East Asia and considered the most important for bioenergy.

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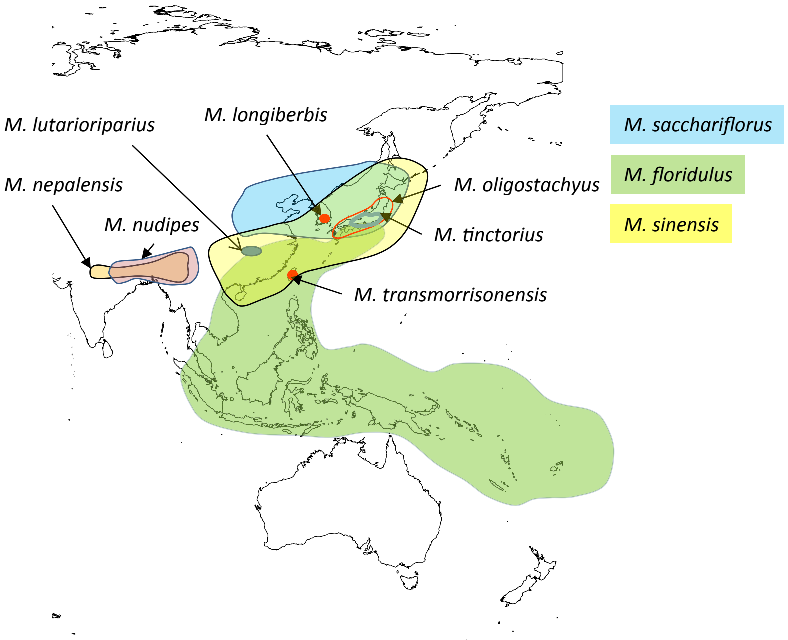

Figure 2.1 Geographical distribution of the major *Miscanthus* species.
Adapted from Ibaragi, Y.Y., Ohashi, H.H, 2004. A taxonomic study of *Miscanthus* section Kariyasua (Gramineae). Journal of Japanese Botany 79 (1), 4–22; Clifton-Brown, J., Renvoize, S., Chiang, Y., et al., 2010. Developing *Miscanthus* for bioenergy. In: Energy Crops, which was compiled based on the information provided by Steve Renvoize (Kew), Yashushi Ibaragi (Japan), Tsai-Wen Hsu (Taiwan), and Qingguo Xi (China).

2.2 Miscanthus Breeding

Initial breeding efforts in Germany in the 1960s focused on producing horticultural varieties with different leaf and stem morphologies. In the late 1980s, further wild collections were made and breeding of miscanthus for bioenergy purposes began. The exploratory crossing of various accessions, mainly from *M. sinensis* and *M. sacchariflorus*, began after the identification of the parents of *M.* × *giganteus* (Greef and Deuter, 1993). The hybrids are being tested across Europe under diverse climatic conditions in various projects (Clifton-Brown et al., 2001; Lewandowski et al., 2016) (Fig. 2.3).

2.2.1 Breeding Targets

For all miscanthus breeding programs, the main objective is to increase the biomass yield with minimal inputs under diverse climatic conditions. In the recent EU project OPTIMISC, new hybrids were identified that can outperform *M.* × *giganteus*, especially

Miscanthus anderss. (1856)

- Generic synonymy
- Sclerostachya (hack.) A. Camus (1922)
- Triarrhena (maxim.) nakai (1950)
- Rubimons B.S. Sun (1997)
- Diandranthus liou (1997)

- Section diandranthus keng (1957,1959)

Lemmas awned
Stamens 2,
Stigma apically exserted

1. Miscanthus nudipes (Griseb.) Hack.1889.
- Erianthus nudipes grisebach 1868:
- Miscanthus brevipilus handel-mazzetti:
- M. Eulalioides keng:
- M. Nudipes ssp. yunnanensis A. Camus:
- M. Szechuanensis keng ex S. L. Zhong:
- M. Taylori bor:
- M. Wardii bor:
- M. Yunnanensis (A. Camus) keng.

Diandranthus brevipilus (handel-mazetti) L. Liou:
- D. Corymbosus L. Liou:
- D. Eulalioides (keng) L. Liou:
- D. Nudipes (griseb.) L. Liou:
- D. Szechuanensis (keng ex zhong) L. Liou:
- D. Taylori (bor) L. Liou:
- D. Tibeticus L. Liou:
- D. Wardii (bor) L. Liou:
- D. Yunnanensis (A. Camus) L. Liou:

2. M. Nepalensis (trin.) Hack. (1889)
- Eulalia nepalensis trin. (1833)
- Diandranthus nepalensis (trin.) L. Liou.

- Section triarrhena (max.) honda (1930)
- Stamens 3
- Lemma awnless

1. Miscanthus sacchariflorus (maxim.) hack. (1887)
- Imperata sacchariflora maxim. (1859)
- Triarrhena sacchariflora (maxim.) nakai.

2. Miscanthus lutarioriparius L. Liou ex Renvoize & S. L. Chen.

- Section miscanthus
- Lemmas awned
- Stamens 3
- Stigmas laterally exserted

- 1. Miscanthus sinensis anders. (1855)
- Miscanthus condensatus hack.
- M. Flavidus honda:
- M. Kanehirai honda:
- M. Purpurascens anders.
- M. Transmorrisonensis hayata.

- 2. Miscanthus floridulus (labill.) Warburg ex K. Schum. & lauterb. (1901)
- Saccharum floridulum labill. 1824; Miscanthus japonicus anders. (1855)

- Section sclerostachya ined.
- Lemma awnless
- Stamens 3
- 1 species

- M. Fuscus (roxb.) benth. (1881)
- Saccharum fuscum roxb. (1820)
- Sclerostachya fusca (roxb.) Camus (1922)

- Section kariyasua ohwi ex hirayoshi.
- Nishikawa & kubono (1956)
- Lemmas awned or awnless
- Stamens 3
- Stigma exserted laterally
- 4 species

- 1. M. Intermedius (honda) honda (1936)
- M. Longiberbis nakai var intermedius honda. (1933)
- M. Tinctorius (steud.) hack. var intermedius (honda) ohwi (1942)
- M. Oligostachyus stapf ssp intermedius (honda) T. Koyama (1987)

- 2. M. Longiberbis(hack.) nakai (1916)
- M. Matsumurae hack. var longiberbis hack. (1904)
- M. Sinensis var longiberbis (hack.) I.C. Chung (1955)
- M. Changii Y.N. Lee (1964)
- M. Oligostachyus var longiberbis (hack.) I.C. Chung (1965)

3. M. Oligostachyus stapf (1898)
- M. Matsumurae hack. (1899)

4. M. Tinctorius (steud.) hack. (1889)
- Saccharum tinctorum steud. (1855)
- Miscanthus sieboldii honda (1930)

Figure 2.2 The phylogenetic relationships based on classical taxonomy between species within the *Miscanthus–Saccharum* complex. The most important for biomass production are *Miscanthus sacchariflorus* (in Triarrhena) and *Miscanthus sinensis.*
Adapted from Clifton-Brown, J., Renvoize, S., Chiang, Y., et al., 2010. Developing *Miscanthus* for bioenergy. In: Energy Crops.

Figure 2.3 Field plots with different miscanthus genotypes grown at the experimental field station “Ihinger Hof,” south Germany.

in suboptimal growing conditions such as drought, cold, or salinity (Lewandowski et al., 2016). The crop dry matter yield and energy yield per hectare, which depends on the energy conversion route taken, are principal criteria to evaluate crop performance for bioenergy (Kiesel et al., 2017). Breeding is attempting to maximize the net energy yield output through improving the resource use efficiency of the crop and the biomass quality for different utilization options, while maintaining a high biomass yield. This, however, involves complex traits, and breeders need to use simpler metrics of whole-season integrated traits, such as stem height and tiller density, to make selections. The most relevant breeding selections are made in plots, but since these are resource-intensive, cheaper spaced plant nurseries are frequently used in the initial screening steps. Biomass quality characteristics are relevant when selecting genotypes for specific uses. However, trade-offs between quality and yield are often observed (Lewandowski et al., 2016). Early-senescing genotypes with low contents of water, ash, potassium (K), and chloride (Cl) are preferred for combustion purposes. However, early-senescing *M. sinensis* genotypes displaying low ash, K, and Cl contents are also among the lowest yielding (Lewandowski et al., 2003). High contents of lignin are desirable for combustion of miscanthus biomass. However, genotypes with lower lignin contents are more suitable for fermentation purposes, such as anaerobic digestion and ethanol production. Presently, *M.* × *giganteus* is field-established by high-cost vegetative propagation methods. Most breeding efforts are currently focusing on seed-based hybrids.

2.2.2 Genetic Resources

The wide geographic distribution of miscanthus in East Asia has resulted in enormous genetic diversity (Fig. 2.2) and consequently phenotypic variation. Molecular phylogenetic distances have been reported for germplasm collections in Taiwan

(Chou et al., 1999; Chou, 2009), Japan (Iwata et al., 2005; Stewart et al., 2009), and China (Xi and Jezowski, 2004; Chen and Renvoize, 2006). This diverse genetic resource is being exploited in breeding programs in Europe (Clark et al., 2015) and the United States. Clifton-Brown et al. (2015) have reported that germplasm collections in Asia form the basis of a breeding program in the United Kingdom, where thousands of exploratory two-parent crosses have been attempted within and between species in diverse accessions. While the flowers of *M. sinensis* and *M. sacchariflorus* have both anthers and stigma (dioecious), most miscanthus genotypes are highly self-incompatible. This ensures that all seed produced results from outcrossing events and therefore lends itself to "hybrid" breeding. This material is presently being further developed in breeding programs and tested at different locations in Europe and the United States (see, e.g., Lewandowski et al., 2016).

2.3 Physiological Characteristics

2.3.1 C_4 Pathway and Resource Use Efficiency

Miscanthus performs photosynthesis by the C_4 pathway. In this pathway, the first compound formed through CO_2 fixation is a 4-carbon organic acid (oxaloacetate) catalyzed by phosphoenolpyruvate carboxylase. The C_4 pathway directly influences the resource use efficiency of the crop (Sage and Zhu, 2011). For example, it contributes toward high water use efficiency through reduced evapotranspiration by keeping the stomata closed for longer and fixing the available CO_2 more efficiently than in the C_3 pathway (Byrt et al., 2011). Although *Miscanthus* is undomesticated, it outperforms many other C_4 species under temperate climatic conditions in terms of resource use efficiency and ability to grow under low-temperature conditions. For example, *M.* × *giganteus* is capable of carrying out photosynthetic activity at temperatures as low as 6°C, even lower than the threshold temperature for maize (Wang et al., 2008). Despite being a C_4 plant, some miscanthus genotypes are cold-tolerant and can survive severe winters (Clifton-Brown and Lewandowski, 2000a).

The aboveground water use efficiency of miscanthus varies greatly depending on climatic conditions. For example, biomass accumulation ranges from 9 to 13 g DM ha^{-1} water under temperate conditions (Beale et al., 1999), but from 3 to 5 g DM ha^{-1} water in Mediterranean conditions (Cosentino et al., 2007). Thus the amount of water required for each kg of biomass accumulation is lower for miscanthus than for maize and sugarcane (Van der Weijde et al., 2013).

Miscanthus achieves high nutrient use efficiency in three ways: (1) low input requirements; (2) recycling of nutrients through litter falling; and (3) translocation of nutrients back to rhizomes. The recycling of nutrients is highly dependent on the efficiency of the translocation process, which in turn is mainly defined by the phenological traits of the genotype and the time of harvesting. Early-flowering genotypes complete the translocation of nutrients more efficiently before frost kills the stems. The nutrient input demand for optimal growth is highly dependent on soil conditions. For each kg of DM yield, miscanthus removes 4.90 g N, 0.45 g P, and 7.20 g

(Cadoux et al., 2012), which is significantly lower than for other C_4 crops such as sorghum, sugarcane, and maize (Van der Weijde et al., 2013).

Radiation use efficiency is shown to vary with temperature and is reduced by water stress. Hastings et al. (2009) used data from Farage et al. (2006) to develop a temperature-related radiation use efficiency model that has a maximum value of 4.8 g biomass dry matter per MJ radiation. This becomes about 2.35 g in temperate climates, as found by Clifton-Brown et al. (2000). Experiments investigating yield response to nitrogen fertilizer application showed that there was little impact, except where either the soil was sand (Clifton-Brown et al., 2001) or where the miscanthus was harvested before senescence (Danalatos et al., 2007). Some miscanthus genotypes have been shown to be conservative users of water, especially under reduced soil water conditions; others such as the current commercial genotype *M.×giganteus* less so (Clifton-Brown and Lewandowski, 2000b).

2.3.2 Tolerance to Abiotic Stresses

Miscanthus has proven to be productive on lower-grade agricultural land, including saline soils (Qian et al., 2014; Lewandowski et al., 2016) and heavy metal-contaminated land (Pidlisnyuk et al., 2014; Barbosa et al., 2015). However, the standard genotype *M.×giganteus* shows limitations with regard to abiotic stresses, especially drought (Clifton-Brown and Lewandowski, 2000b). Therefore the objective of the EU project OPTIMISC was to identify relevant traits and mechanisms for the abiotic stresses drought, salinity, chilling, and frost, which are relevant for miscanthus production (Lewandowski et al., 2016).

Genotypes that outperformed *M.×giganteus* under drought conditions were identified among *M. sacchariflorus* as well as *M. sinensis* types and hybrids. Drought tolerance was found to be provided through a combination of traits (Lewandowski et al., 2016).

Salinity-tolerant genotypes that tolerate electrical conductivity values of up to 2.5 without major yield losses were identified among *M. sacchariflorus* and *M. sinensis* types. *M.×giganteus* did not prove salinity-tolerant. The best-performing genotypes were found to use a mechanism that actively prevents ions from accumulating in the leaves and thus minimizes damage to essential physiological processes such as photosynthesis (Lewandowski et al., 2016). Generally, plants with larger rhizomes were found to be more salinity-tolerant than plants with smaller rhizomes (Chen et al., 2017).

Frost tolerance assessment revealed that there are more tolerant genotypes than *M.×giganteus* available among the *M. sinensis* and hybrid types (Lewandowski et al., 2016). Cold and frost tolerance are major mechanisms that allow the range of European miscanthus production to be extended further north and east (Fig. 2.10).

2.4 Global Miscanthus Production and Use

Currently, approximately 123,000 ha are used for miscanthus biomass production globally. The largest area is found in China, where about 100,000 ha of *Miscanthus lutarioriparius* grow wild at Dongting Lake. Biomass yields are approximately

Table 2.1 **Present commercial miscanthus production areas and biomass applications (Statistik Austria, 2016; Lewandowski et al., 2016; Lewandowski, 2016; Furtlehner, 2017; Heaton, 2017)**

Country	Area (ha)	Genotype	Biomass application
China	**100,000**	*Miscanthus lutarioriparius*	Paper making, building materials, pickles
Europe	**19,050**		
UK	10,000	*Miscanthus × giganteus*	Cofiring in power generation
Germany	4,000	*M. × giganteus*	Heating, building materials
France	4,000	*M. × giganteus*	Heating, fuel for feed drying and pelleting (corn, grass, alfalfa, etc.), animal bedding, building material (lightweight concrete)
Switzerland	500	*M. × giganteus*	Building materials
Poland	500	*M. × giganteus*	Building materials, biocomposites
Denmark	50	*Miscanthus sinensis*	Thatching
Austria	1000	*M. × giganteus*	Combustion (mainly heat), horse bedding, mulching
US	**3,200**	*M. × giganteus*	Heat and power generation, animal bedding, fiber additive for animal feed

$12\,\mathrm{t\,ha^{-1}\,a^{-1}}$, mainly used for paper making (Xue et al., 2015a), but also as building material and for food. In Europe, there are about 20,000 ha of miscanthus, mostly in the United Kingdom, France, and Germany (Table 2.1).

In the United Kingdom, the main application of miscanthus biomass is electricity generation in dedicated straw-burning power stations. In Germany, thermal conversion in small-scale heating plants is prevalent. Material uses include building materials and biocomposites. Apart from several hectares of *M. sinensis* used for thatching in Denmark, only one genotype, *M. × giganteus*, is cultivated commercially in Europe. *M. × giganteus* is also grown on an estimated 3200 ha in the United States (Table 2.1).

2.4.1 Energetic Routes

2.4.1.1 Combustion

In Europe, a large proportion of miscanthus biomass is utilized for combustion to produce heat, electricity, or combined heat and electricity. For heating purposes, it is used for direct firing of thermal power stations and in small-scale biomass burners. Currently, a market is also being developed for miscanthus pellet-fired heating boilers. The generation of electricity and combined heat and power (CHP) mostly requires large-scale application, e.g., Drax power plant. The suitability of biomass for combustion depends on the contents of ash, potassium, and chloride and the ash melting behavior (Iqbal and Lewandowski, 2016). Miscanthus biomass has some quality limitations for combustion mainly because of its high potassium and chloride contents compared to wood biomass. The K content has been reported to vary from 0.11% to 1.2% DM and Cl content from 0.03% to 0.16% DM, depending on genotype and harvesting time (Iqbal and Lewandowski, 2014; van der Weijde et al., 2017). The high potassium content leads to low ash melting temperatures in miscanthus-based combustion and the chlorides can form corrosive compounds that potentially damage the boilers. A high ash melting point is important for most of the common (low-/medium-scale) biomass combustion technologies, which were developed for wood biomass and require a minimum ash melting temperature of 1200°C for safe operation. However, combustion technology is also available that can handle lower ash melting temperatures (e.g., fluidized bed combustion, boilers with water-cooled grates) or that actually requires low ash melting temperatures [e.g., large-scale (coal) boilers with liquid ash discharge]. For *M.* × *giganteus*, ash melting at 900°C has been reported (Iqbal and Lewandowski, 2016). Significant variation in ash melting points were found among different genotypes grown in Germany (Iqbal and Lewandowski, 2014). In the Netherlands, some *M. sinensis* genotypes tested showed no ash melting up to 1100°C (van der Weijde et al., 2017). The variation offers an opportunity to both select appropriate genotypes and develop the harvest and postharvest techniques to maximize ash fusion temperature. There are various options to optimize biomass quality along the production chain, especially at field level. For example, harvesting time has a strong influence on inorganic constituents of biomass, which subsequently affect ash melting behavior. For combustion purposes, March is considered the optimal harvesting time in temperate regions to deliver biomass with low potassium, chloride, ash, and moisture contents (Iqbal and Lewandowski, 2014).

2.4.1.2 Biogas

The use of miscanthus biomass for biogas production is an application currently being explored and is not yet state of the art in practical biogas plants. There are several challenges that need to be overcome before miscanthus can be regarded as a major crop for biogas production. The main one is to find the optimum harvest time, allowing a high yield per area and supplying suitable biomass quality, while maintaining the long-term productivity of the crop. The latter is especially challenging because a spring harvest is unfavorable for anaerobic digestion of miscanthus biomass. Biomass losses over the winter reduce the biogas yield. In addition, lignin content increases over the fall and winter and leads to a lower biomass quality for anaerobic digestion, as lignin is negatively correlated with specific biogas yield (Kiesel and Lewandowski, 2017). For this reason, miscanthus should be green-harvested before winter. This delivers a higher biomass yield and quality but risks compromising the yield in the following year. October was identified as a feasible harvest date for *M.* × *giganteus* in southwest Germany, supplying high and stable biomass yields of approximately 25 t DM ha^{-1} over several years and a sufficient specific methane yield of 247 mL $(\mathrm{g\,oDM})^{-1}$

(Kiesel and Lewandowski, 2017). Interestingly, a harvest date in late October is aligned with peak biomass yield and therefore allows a high productivity per area of approximately 6000 m^3 CH_4. The biomass quality for biogas production decreases as the vegetation period progresses, due to the lignification process. This means an earlier harvest (e.g., August) would be more desirable from a quality point of view, but cannot be recommended for *M.* × *giganteus* on account of significant yield reduction the following year. An early green harvest would require genotypes with improved green-cut tolerance, which have not yet been identified. Green-cut tolerance is mainly associated with relocation of carbohydrates to the rhizome, which are required for sprouting and regrowth in the following spring (Kiesel and Lewandowski, 2017; Purdy et al., 2015). This means genotypes with improved green-cut tolerance need to start and complete the relocation of carbohydrates earlier. Possible influencing factors for this process are flowering and active senescence. Novel genotypes also offer the potential to deliver less lignified biomass, supplying higher specific methane yields of up to 300 mL $(g\,oDM)^{-1}$ (Kiesel et al., 2017). However, such genotypes would also require a very high biomass yield, since this is still the most important factor influencing net energy yield.

In Europe, *M.* × *giganteus* is among the highest-yielding genotypes and still the only commercial available variety. For this reason, it is recommended for biogas utilization when green-harvested in October. To maintain the long-term productivity of the crop, the nutrients removed by the harvested biomass need to be replaced by application of digestate or fertilizer. In contrast to commercial application, the potential analysis studies mentioned previously were performed with milled biomass. Milling is a pretreatment that can significantly influence the specific methane yield and the velocity of methane production. For this reason and to avoid process interference (e.g., floating layers), a suitable pretreatment of the miscanthus biomass is recommended. Various pretreatment technologies have been described in the literature, such as extrusion, milling, ultrasound, and white and brown fungi treatments (Frydendal-Nielsen et al., 2016; Patinvoh et al., 2017). In practice, such pretreatment technology is increasingly used, since this allows utilization of cheaper input substrates, e.g., agricultural residues. Due to its perennial nature, high yield potential, and improving establishment methods, miscanthus is a promising crop for the provision of large quantities of low-cost biomass for anaerobic digestion.

2.4.1.3 Liquid Fuels and Biochemicals

Miscanthus is not a typical crop for liquid fuel production (first-generation biofuels), since it contains no extractable oils and very little sugar. Its biomass can be characterized as lignocellulosic, with high cellulose and hemicellulose contents (cellulose + hemicellulose = holocellulose). The content of cellulose, hemicellulose, and lignin can be influenced by genotype choice and harvest time of the biomass (Hodgson et al., 2011; van der Weijde et al., 2017). Due to the increasing number of full-scale, second-generation biofuel plants worldwide, miscanthus has the potential to become a major biofuel crop.

Second-generation biofuel refineries can be classified according to the conversion routes used: (1) thermochemical (e.g., gasification and pyrolysis) and (2) biochemical.

In the biochemical conversion route, the biomass is pretreated and the cellulose and hemicellulose are hydrolyzed enzymatically into C6 and C5 sugars, respectively. In recent years, yeast strains have been developed that can convert not only C6 but also C5 sugars into ethanol, allowing a larger part of the holocellulose to be utilized for biofuel production. While the biochemical conversion route is only able to utilize holocellulose, the thermochemical conversion route can also convert lignin into biofuels. For this reason, thermochemical conversion routes are usually applied for the processing of wood or woody raw materials, while biochemical conversion routes are used more for agricultural residues, such as wheat and maize straw, which have a lower lignin content. Miscanthus provides a suitable supplement to such residues because it is harvested in spring at a time when no other residues are available (e.g., wheat straw in summer, maize straw in the fall). Long and costly storage periods can be avoided through the combination of these three raw material sources. The suitability of novel miscanthus genotypes for bioethanol production has been reported in the literature, indicating the large potential of this crop (Kärcher et al., 2015, 2016; van der Weijde et al., 2017; Kärcher et al., 2016).

In addition to biofuel production, the conversion of biomass into platform chemicals for use in various applications, including bioplastics, is currently a promising field of R&D, aiming to establish the bioeconomy in the chemical industry. Both conversion pathways are suitable for biochemical production: e.g., the thermochemical pathway can be applied to produce 5-hydroxymethylfurfural and the biochemical pathway to produce isobutanol. This allows a high-value application of miscanthus biomass, which at the same time can contribute to securing the biomass demand of a growing bioeconomy.

2.4.1.4 Material Uses

The largest amount of miscanthus biomass is produced in China from *M. lutarioriparius* growing wild in a seminatural habitat and harvested for paper making (see Fig. 2.4) (Xue et al., 2015a). In China, miscanthus biomass is also used as building material and for food.

Figure 2.4 *Miscanthus lutarioriparius* growing at Dongting Lake (China) and transport of biomass to the paper mill.
Photos: Xue Shuai and Sai Yang, Hunan Agricultural University.

Building and packaging materials are the most prevalent material uses of miscanthus biomass in Europe. Fig. 2.5 shows examples of bricks, fiberboards, plant pots, and packaging materials produced by Gießereitechnik Uwe Kuehn, Germany (www.miscanthus-buscheritz.de). Due to its high water absorption capacity,

Figure 2.5 Various products made from miscanthus biomass by Gießereitechnik Uwe Kuehn. Photos: Olena Kalinina, University of Hohenheim; Karl-Müller Sämann, Agency for Sustainable Management of Agricultural Landscape (ANNA).

Figure 2.6 Lightweight concrete based on miscanthus biomass.
Photo: Danièle Waldmann, Universität Luxemburg.

miscanthus fibers are especially suited for packaging material that needs to absorb liquid. This feature has been exploited to develop an air transport packaging material for liquids.

Fig. 2.6 shows lightweight concrete based on miscanthus aggregate, produced by Waldmann et al. (2016). Miscanthus is a useful aggregate for concrete mixtures due to the silicon layer on its outer shell (Waldmann et al., 2016). Calcium chloride was found to be the most effective mineralizer, giving the cement high compressive strength and good bonding between the miscanthus aggregates. The compressive strength of this concrete is comparable to other lightweight concrete mixtures and shows good thermal conductivity performance (Waldmann et al., 2016). Lightweight concrete based on miscanthus biomass has several advantages over mixtures based on sand or gravel, including better insulation properties, improved protection against overheating in summer, and high durability. The latter is due to the good mineral bonding ability of the miscanthus material (Waldmann et al., 2016).

2.4.1.5 Animal Bedding

In France, miscanthus is used as litter for turkeys with good results (www.novabiom.com). It has also been used in Wales for overwintering sheep and as bedding for horses in Ireland. Compared to conventional bedding on straw, deep miscanthus litter has the advantage of better water absorption and ammonia adsorption, avoiding the need for

Figure 2.7 *Left*: Turkeys on miscanthus bedding. *Right*: Healthy feet of turkeys bedded on miscanthus.

litter renewal during the turkey growth period. In addition, turkeys are healthier on miscanthus than on straw bedding with fewer pests and leg injuries being observed (DeBruyn, 2015) (Fig. 2.7).

Investigations have also shown the suitability of miscanthus as bedding material for cows and horses (Van Weyenberg et al., 2015; Rauscher and Lewandowski, 2016). A 4-week trial comparing miscanthus and straw bedding for horses identified the same advantages of miscanthus as for turkey bedding, in particular with regard to the high standards of hygiene (Rauscher and Lewandowski, 2016). A comparison of miscanthus, straw, and woodchip beddings also showed that miscanthus bedding produces less manure mass and volume with higher bulk density. This results in lower volume requirements for manure storage and less time needed for mucking out. However, miscanthus bedding is more expensive due to higher material costs and additional coarse feed requirements (Rauscher and Lewandowski, 2016). For this reason, miscanthus horse bedding is particularly recommended for professional equestrian sport, horse farms that need to reduce manure volumes, and owners of allergic horses (Rauscher and Lewandowski, 2016).

2.4.1.6 Food and Feed

In China, the young shoots of wild miscanthus stands are harvested in spring to be made into pickles (see Fig. 2.8). Approximately 5300 t of pickled miscanthus shoots were produced in 2014, with a production value of 0.5 billion CNY (Xue et al., 2015a). The main limitation to the development of this industry is the short harvest period (only 2–3 weeks) of the young shoots. Nevertheless, miscanthus pickle making is still vigorously promoted by the local government and had a target of producing 20,000 t pickles in 2015 (Xue et al., 2015a).

Chlorophyll and protein (for food uses) can be extracted from miscanthus biomass before it is processed for other applications, such as biogas (Lewandowski et al., 2016). The contents of both chlorophyll and protein depend on the harvest date of the biomass and are higher with earlier (green) harvest. For example, an *M. sinensis* genotype harvested in early July reached a chlorophyll content of up to 3.5% DM in

Figure 2.8 Processing young shoots of miscanthus in China.
Photo: Sai Yang, Hunan Agricultural University.

leaves and 2.8% DM in stems, and protein contents of 12% (leaves) and 11% (stems) (Lewandowski et al., 2016).

Miscanthus biomass is also used as a fiber additive in ruminant feed and even in some dog food (Heaton, 2017). In the Netherlands, miscanthus is considered a useful addition to protein-rich grass, improving cows' digestion and thickening the dung (http://www.bkcbv.nl/miscanthus-rantsoen/#).

2.5 Productivity of Miscanthus Across Europe

Yields reported from field trials across Europe with the standard genotype *M.×giganteus* vary according to location and harvest date (see Fig. 2.9). Generally, yields are lower on sites with water limitations or other abiotic stresses. They also decrease when harvest is delayed after peak yield. However, to obtain the best biomass quality for use as a combustion fuel, miscanthus is normally harvested in spring after full senescence and relocation of nutrients to the rhizomes and has had time to dry in the field to <14% moisture.

The EU projects EMI and OPTIMISC investigated the productivity of novel miscanthus genotypes (in comparison to *M.×giganteus*) across Europe (Lewandowski et al., 2003, 2016). Based on field measurements at the different EMI locations, the model MISCANFOR was developed to predict miscanthus productivity under different conditions (Hastings et al., 2009). In the OPTIMISC project, 15 miscanthus genotypes were compared with an *M.×giganteus* reference scenario and the model expanded to include new data from the novel genotypes (Nunn et al., 2017). The results predict a large miscanthus productivity potential across Europe and a possible extension of the cultivation area (compared to a scenario with the standard genotype *M.×giganteus*) to the north and east, once novel genotypes are available (Fig. 2.10).

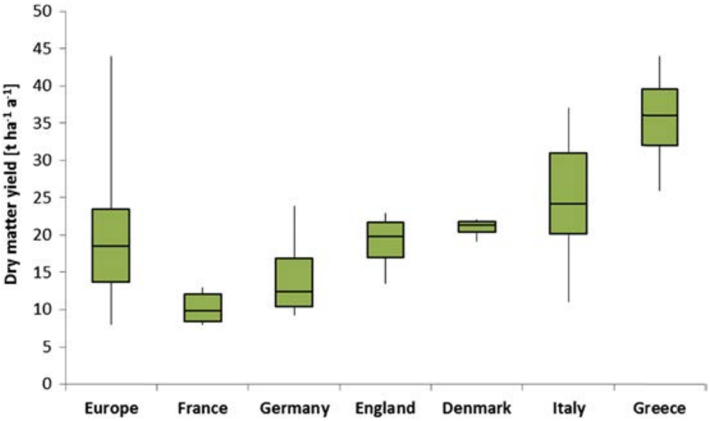

Figure 2.9 *Miscanthus* × *giganteus* yields reported for early spring harvest in Europe (Ercoli et al., 1999; Lewandowski et al., 2000; Clifton-Brown et al., 2001; Price et al., 2004; Mardikis et al., 2004; Stampfl et al., 2007; Danalatos et al., 2007; Cosentino et al., 2008; Christian et al., 2008; Angelini et al., 2009; Mantineo et al., 2009; Strullu et al., 2011; Gauder et al., 2012; Larsen et al., 2014; Shield et al., 2014; Kalinina et al., 2017).

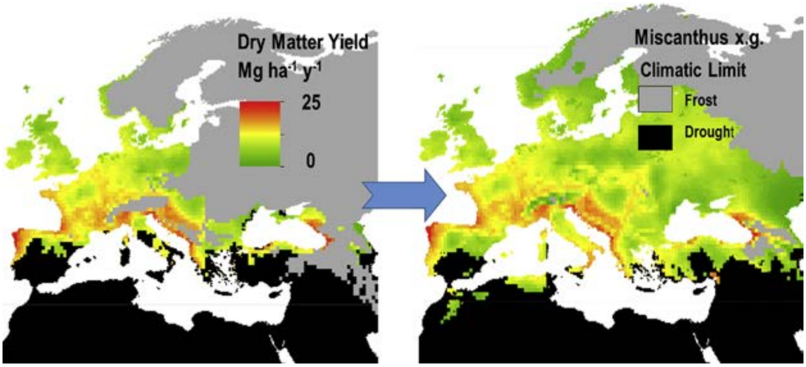

Figure 2.10 Bioclimatic envelope of *Miscanthus* × *giganteus* showing limit of frost and drought tolerance. Excluded area is shown in light gray or black. *Left* shows the original (Hastings et al., 2009) bioclimatic envelope and *right* shows the revised estimation resulting from the research in OPTIMISC. The crop yield prediction for *M.* × *giganteus* is displayed on a scale from 0 Mg ha^{-1} (dark green—gray in print versions) to 25 Mg ha^{-1} (red—dark gray in print versions). The new cold limit considers the data from in-field soil temperature measurements and the overwinter survival success. The new drought limit is based on observed in-field drought responses and water balances with estimates of plant-available water derived from depth and soil texture measurements. This high-level analysis does not identify the marginal or best lands within the grids where the yields may be lower or higher than those indicated.

2.6 Agronomy

2.6.1 Propagation and Establishment

There are several options for propagating miscanthus. The propagation method used has a direct influence on both survival rate and production costs. As a sterile clone, *M.* × *giganteus* can only be propagated vegetatively and in practice this is mostly done by rhizomes. Xue et al. (2015b) identified the following methods for miscanthus establishment:

- Direct planting of rhizomes harvested in a mother field (1900–3400€ ha^{-1});
- Plantlets produced in plugs from rhizome cuttings (4300€ ha^{-1});
- Nodes produced in modules (4000€ ha^{-1});
- Through seeds (costs not yet known);
- Through micropropagation (6000€ ha^{-1}).

Miscanthus breeding programs aim to produce viable seeds because it is anticipated that seed-based establishment methods will prove most effective for scaling up miscanthus production. Seed establishment has the advantages of lower costs, higher propagation rates, quick access of farmers to novel genotypes, and phytosanitary safety. The British company Terravesta is developing seed-based propagation methods using "plug plants" with partners in large-scale horticulture. In cool climates and on marginal soils, establishment rate and reliability with plugs have been vastly improved using mulch films originally developed for maize.

2.6.2 Weed Management and Crop Protection

As a perennial C_4 grass, miscanthus offers a number of environmental benefits, one of which is the overall low use of chemicals for weed management and crop protection. However, effective weed control is very important during the first year to avoid negative impacts on the establishment success of the crop and competitiveness in subsequent years. In the first year, mechanical weeding can be performed between the rows and, once the crop is well enrooted, on the complete field. Herbicides for miscanthus have also been available for some years now, most of which originate from maize cultivation. Active substances that can be used for miscanthus include: dimethenamid-P, pendimethalin, bromoxynil, mesotrione, tritosulfuron, dicamba, and MCPA. A good strategy has proved to be application of soil herbicides (e.g., dimethenamid-P, pendimethalin) after the planting of rhizomes or plantlets, followed by an application of mainly leaf-active herbicides (e.g., a combination of mesotrione and bromoxynil or tritosulfuron and dicamba) some weeks later. On fields with high grass weed pressure, rimsulfuron is also a good option, but here application conditions need to be suitable and the crop growing well, otherwise the herbicide may damage the miscanthus. It is especially important to ensure low weed competition in spring and early summer. Weeds that grow in late summer can be tolerated to a certain extent and removed in the following early spring by application of glyphosate. Glyphosate application is only possible if strong frosts occurred over winter and the crop has not started to regrow (no new shoots) in spring. If stems from the previous year have not been completely killed by winter frosts or new shoots are already visible, glyphosate application will lead to heavy damage and plant losses in the crop. Once miscanthus is established, it competes well with weeds due to its rapid growth in spring and the shading of the soil. Additionally, the leaf fall creates a mulch layer, which contributes to weed control.

Under European conditions, the incidence of pests and diseases is low and to date only a few miscanthus-specific diseases have been reported (e.g., the fungal pathogen stagonospora, aka Miscanthus blight). In East Asia, where miscanthus is indigenous, the stem borer and miscanthus streak virus have been found in a few accessions (Clifton-Brown and Luis Muir, IBERS Aberystwyth, unpublished). In practice, no measures for active pest or disease control are required for miscanthus production in Europe.

2.6.3 Nutrient Requirements and Fertilization

Miscanthus is a resource-efficient crop on account of efficient nutrient recycling and active nitrogen fixation (Cope-Selby et al., 2017). Recommendations on nutrient fertilization vary greatly depending on soil conditions and nutrient offtake. For example, Iqbal et al. (2015) found the response to N fertilization to be nonsignificant in terms of biomass yield when N application was increased from 40 to 80 $\mathrm{kg\,ha^{-1}}$. Other studies reported no response to N fertilization (Christian et al., 2008; Cadoux et al., 2012; Van der Weijde et al., 2013). For late-harvested (March) miscanthus stands, it is recommended to apply N fertilizer doses of 50 $\mathrm{kg\,ha^{-1}\,a^{-1}}$ on sandy soils or soils lacking organic substances. Miscanthus stands on heavy soils that are rich in organic substance do not require N fertilization. Early-harvested miscanthus with high N content requires more N fertilizer. In general, fertilizer application should be based on calculations to compensate nutrient withdrawal by the harvested biomass.

2.6.4 Harvesting and Logistics

Harvesting miscanthus is a fuel- and labor-intensive process, but varies depending on the choice of harvesting procedures. The harvesting procedure affects the yield, production costs, and environmental performance of the whole production chain. In the United Kingdom, France, and Germany, miscanthus chips are produced from *M.×giganteus* using self-propelled forage harvesters (as used for maize) in an early spring (February to April) harvest when the biomass has moisture contents below 20%. The chips can be stored well in covered storage. However, miscanthus chips have a number of drawbacks, such as low bulk density (150 $\mathrm{kg\,m^{-3}}$), low fuel mass in combustion chambers, and potential bridging and clogging in automated feed systems (Lewandowski et al., 2016).

Another harvesting procedure for miscanthus is the “mow and bale system” (Meehan et al., 2013). This has some advantages despite the additional operation. The forage harvester cuts the miscanthus into a swath faster and uses less fuel than chipping. If the miscanthus is not dry enough, it can be air dried in the field to 14% and then baled when it can be safely stored for a long period. Bales have a density of 350 $\mathrm{kg\,m^{-3}}$ so they are easier to transport. In addition, straw-burning power stations such as Brigg in the United Kingdom are designed to take large Heston bales directly as fuel (Nunn et al., 2017).

Miscanthus biomass can also be pelleted. Slight adjustments to the machinery normally used for wood pellets are needed for miscanthus biomass to avoid overheating of the press. There are differences in pelletability of biomasses from different miscanthus genotypes. In pelleting trials, *M.* × *giganteus*, with its hard, stiff stems, was the most difficult to pellet, but it gave the highest pellet bulk density of 810 g L^{-1} (Lewandowski et al., 2016). The energy costs of large-scale pellet production can vary from 40 to 80€ t^{-1} pelleted biomass, at a capacity of approximately 3 t h^{-1}. This process consumes 3%–6% of the pellet fuel energy.

2.7 Biomass Production Costs

Miscanthus biomass production costs on a tonnage basis mainly depend on the yield harvested, but also on the costs of production factors (such as land and labor), the establishment and harvesting methods, and the need for densification, storage, and transport (Bullard, 2001; Smeets et al., 2009). For the only commercially grown genotype, *M.* × *giganteus*, crop establishment is the dominant cost factor at around 3000€ ha^{-1} (see Section 2.6) and the high initial investments are a deterrent for many farmers to produce miscanthus. Operational costs for fertilization, harvest, storage, and land have been calculated (for German conditions) as 809€ ha^{-1} a^{-1} for a chip-based value chain and 889€ ha^{-1} a^{-1} for a bale-based value chain (Neumann, 2007). Harvesting costs account for 44% and 52%, respectively, of these operational costs.

A study (Lewandowski et al., 2016) has assessed miscanthus biomass supply costs including the production, densification, and transport of biomass from the farm to the unit where it is combusted or processed into ethanol or insulation material. These range from 78€ per tonne dry mass of chips (for local, small-scale production) and 79€ per tonne of silage (50% water) for biogas production, up to about 140€ per tonne dry mass of bales for the production of insulation material, ethanol, and pellets. The costs were assessed for a range of novel genotypes grown at different locations across Europe and at yield levels of 10–16 t DM ha^{-1} a^{-1} (Wagner and Lewandowski, 2017).

The three main potentials for the reduction of future miscanthus biomass production costs are: (1) higher yields through breeding of more stress-tolerant and higher-yielding genotypes as well as optimization of crop management; (2) reduction of establishment costs through development of seed-based establishment methods; and (3) optimized, efficient, and low-loss harvesting methods providing high-quality biomass.

2.8 Ecological Performance

As miscanthus is not native to Europe or the United States, there are concerns about uncontrolled spreading of this crop. There are two potentially relevant pathways for such spreading: (1) via creeping rhizomes and (2) via seed.

Creeping rhizomes have been observed in several *M. sacchariflorus* genotypes, which should therefore be excluded from commercialization (Lewandowski et al., 2016).

Genotypes tested in the EU OPTIMISC field trials that produced viable seeds belonged either to *M. sinensis* species or *M. sinensis* × *M. sacchariflorus* hybrids (Lewandowski et al., 2016). The germination rate varied strongly between genotypes and was found to be especially low in Russia (Moscow area), where the vegetation period was short and long-day conditions retarded the transition to flowering, preventing complete seed ripening (plant senescence occurs earlier). Spreading via seeds was carefully monitored in these trials. Volunteer miscanthus seedlings were only found in temperate climates at sites in the Netherlands and Germany. No accidental spreading via seeds was observed at any of the more southerly or more northerly locations. In the south, seed germination in the field was possibly prevented by drought conditions, and in the north by low temperatures and a shorter vegetation period. It was therefore concluded that spreading via seeds in miscanthus—relevant for *M. sinensis* and *M. sinensis* × *M. sacchariflorus* hybrids—can be prevented by careful choice of genotype. Therefore, genotypes should be recommended that either do not form fertile seeds or that are unable to establish via seed due to the climatic conditions of a specific site.

2.8.1 Land Restoration (Phytoremediation)

On account of its efficient nutrient recycling and low input requirements, miscanthus has the potential to grow on marginal lands. For this reason, it is of interest for growing on contaminated land for the purpose of soil remediation. One study that investigated the cultivation of miscanthus on polycyclic aromatic hydrocarbon (PAH)-contaminated land showed it to have a positive impact on PAH degradation (Didier et al., 2012). Another study that tested the use of miscanthus in buffer strips to control nitrate leaching and avoid groundwater contamination showed positive results with 60%–70% reduction in nitrate leaching (Gopalakrishnan et al., 2012). It can also be grown for the purpose of phytoextraction or phytostabilization of soil contaminants. For example, it has the potential to remediate zinc (Zn)-contaminated soils through phytoextraction (Korzeniowska and Stanislawska-Glubiak, 2015), with *M. sinensis* being the most suitable genotypes because they show no significant decrease in biomass accumulation in Zn-contaminated soils (Barbosa et al., 2015). Other contaminants, such as barium (Ba) and nickel (Ni), can also be targeted for soil remediation. Another study testing miscanthus on heavy metal-contaminated soils showed that it can help to avoid groundwater contamination through phytostabilization of heavy metals (Barbosa et al., 2015).

As miscanthus is a perennial energy grass, it can contribute toward soil humus accumulation over the years. Long-term field trials from 9 to 15 years have reported a carbon sequestration potential ranging from 0.2 to 0.6 $\mathrm{t\,ha^{-1}\,a^{-1}}$ (Pidlisnyuk et al., 2014). Another study has found the carbon sequestration potential of miscanthus to be double that of willow (Borzecka-Walker et al., 2008).

2.8.2 Life Cycle Assessment

Various life cycle assessment (LCA) studies have been conducted to analyze the environmental performance of different miscanthus-based value chains from crop production through to utilization of the biomass. These assessments have shown environmental advantages over the use of fossil resources in several impact categories including global warming potential and fossil fuel depletion (Felten et al., 2013; Kiesel et al., 2016; Meyer et al., 2016; Wagner and Lewandowski, 2017). However, net negative impacts on the environment can also occur, for example, in the categories terrestrial acidification and freshwater eutrophication. The main hot spots identified in the miscanthus cultivation process are nitrogen fertilizer production and fertilizer-induced emissions such as N_2O (Kiesel et al., 2016). There is a high correlation between miscanthus yield and both greenhouse gas (GHG) emission savings and energy savings (Meyer et al., 2016). Therefore, the mitigation potentials are lower on less productive sites such as marginal land.

In the EU project OPTIMISC, new miscanthus genotypes were grown on several sites across Europe and their environmental performance was assessed for six utilization pathways. The results shown here are for the value chain "*production of insulation material based on miscanthus biomass*," which showed comparably high net benefits and low net impacts. This is partly due to the substituted fossil reference (in this case glass wool), which is very energy-intensive in the production process. The main reason, however, is the possible "cascade use" of the biomass in this value chain: it is first used to produce the insulation material, which—after a use phase of several decades—is then incinerated to produce power and heat in a CHP plant. The highest biomass yields as well as the highest GHG- and fossil-energy saving potentials (up to 30.6 t CO_{2eq} ha^{-1} a^{-1} and 429 GJ ha^{-1} a^{-1}, respectively) were achieved for miscanthus grown on nonmarginal sites in Central Europe. On marginal sites limited by cold (Moscow/Russia) or drought (Adana/Turkey), savings of up to 19.2 t CO_{2eq} ha^{-1} a^{-1}, 273 GJ ha^{-1} a^{-1} (Moscow), 24.0 t CO_{2eq} ha^{-1} a^{-1}, and 338 GJ ha^{-1} a^{-1} (Adana) can be achieved (Lewandowski et al., 2016). These results again emphasize the importance of yield as a key parameter influencing environmental performance, but they also highlight the fact that, from an environmental point of view, it can make sense to use marginal land for biomass production.

The results given by LCAs on possible savings of GHG emissions and fossil fuels through use of miscanthus biomass very much depend on the fossil reference applied and thus on the anticipated utilization (Meyer et al., 2016; Wagner and Lewandowski, 2017). Higher savings can be achieved when the miscanthus biomass substitutes materials or energy carriers with a high GHG emission or fossil use burden.

Carbon mitigation costs of 83€ per tonne avoided CO_{2eq} were given when electricity is produced in a medium-scale 5 MW CHP power plant, assuming that the biomass is supplied as bales or pellets over a transport distance of 400 km (Lewandowski et al., 2016). How high the carbon mitigation costs are also depends on the anticipated use of the miscanthus biomass. They can range from −78€ per tonne avoided CO_{2eq} for small-scale combustion of chips for heating purposes to +94€ per tonne avoided CO_{2eq} for medium-scale biogas production (Lewandowski et al., 2016).

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Switchgrass: From Production to End Use

3

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3.1 Introduction

Switchgrass is a C_4 warm-season erect perennial grass native to North America, which at the beginning of the 1980s was selected as a potential energy crop for the United States (Wright and Turhollow, 2010). A decade later, switchgrass was also adopted "as an ideal biomass crop" by Europe (Christian and Riche, 2001), Canada (Samson et al., 2005), and China (Yue et al., 2017). Nowadays, several studies have been reported in other areas around the globe (South America, Asia, Australia, and Africa) (Parrish et al., 2012).

The current switchgrass has a high water use efficiency (WUE) attributed to its C_4 cycle, and therefore to its efficient photosynthetic pathway. It has a deep root system that may facilitate access to deep, moist soil layers, which could significantly contribute to enhance transpiration efficiency and/or adjust the water needs of the plant. Upland ecotypes are considered better adapted to drought conditions compared to lowland ecotypes.

When switchgrass was first selected as an energy crop it had been managed as a forage crop (Sanderson et al., 2006). Over time, management was adjusted and a high number of research articles were published in this direction. The crop is established by seed (200–400 pure live seeds per m^{-2}), while several distances between the rows have been tested varying from 15 to 70 cm. Successful establishment is a key factor to ensure high yields and a lifespan longer than 15 years (Myers and Dickerson, 1984). Most studies agreed that harvesting should be done a few weeks after a killing frost (Vogel et al., 2011; Mitchell et al., 2010a,b). Harvesting could be done with adjustments to the harvesting machines used for hay harvesting (Mitchell et al., 2008) and harvesting material can be baled in large round bales and/or square bales.

Switchgrass has been proposed as an ideal lignocellulosic crop for energy production (through thermochemical and/or biochemical processes) due to its high biomass productivity and its ability to be cultivated successfully on marginal land. Nowadays, switchgrass is also being investigated as a source of nonenergy for fiber or pulp for

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paper, for biomaterials, and for bioproducts. Moreover, native prairie grasses such as switchgrass are commonly used in phytoremediation strategies.

In this chapter, knowledge of switchgrass from production to end use is presented and discussed. The chapter covers the following topics: origin and distribution, breeding, plant physiology, crop management, crop productivity worldwide, harvesting, storage, and end use.

3.2 Origin and Distribution

Switchgrass (*Panicum virgatum* L.) is a C_4 warm-season perennial grass belonging to the Poaceae family. It resembles a bunchgrass and it spreads slowly by seeds and rhizomes. The plant has erect stems with a height that could vary from 0.5 to 2.7 m. At inflorescence, open panicles 15–50 cm long are developed on the top of the tillers. Switchgrass plants have a deep root system that can be up to 3 m in depth.

The *Panicum* genus contains more than 450 species rather heterogeneous. Switchgrass is native to North America and thus it is considered a New World species, where it occurs naturally from 55°N latitude in Canada southward into the United States and Mexico (Waller and Lewis, 1979; Jefferson et al., 2002). Switchgrass first appeared 2 million years ago (Parrish et al., 2012) and thereafter radiated and adapted across major portions of the North American continent (Huang et al., 2011). In the course of these 2 million years, most linkages would have been driven into extinction or moved into more southern and ice-free climates. The survivors would presumably have followed the ice northward during interglacial periods (Zhang et al., 2011). Thus the species continued to evolve throughout the years resulting in two district ecotypes (lowland and upland) with widely varying ploidy levels. When Europeans arrived in the New World, switchgrass distribution ranged from central to eastern North America (Hitchock, 1935).

The birth of switchgrass as a real crop, based on the references that can be found, happened a century ago. Switchgrass history as a real crop planted and/or studied in monoculture counts dates back only a few decades. Initially, switchgrass was of interest as a member of prairie ecosystems and slowly became popular as a potential forage crop and then for other uses when grown in monoculture as a true crop. Switchgrass began to emerge from the anonymity of being “just” a prairie grass in the 1940s. Thereafter, a number of studies have dealt with switchgrass as a forage crop with regard to plant agronomy or as animal nutrition. In the 1980s a large number of studies were reported and although the majority of them dealt with its forage value and breeding there were a few reports that dealt with reclamation, erosion control, and diseases.

Also in the 1980s, switchgrass was identified as a candidate energy crop for the United States by the US Department of Energy (DOE) (Wright and Turhollow, 2010; Wright, 2007). It has been described as a native crop with an extensive areal range in North America that could produce significant amounts of lignocellulosic biomass (20 Mg ha^{-1}) and could be grown on marginal croplands (droughty, infertile, and eroded soils). After DOE funding, switchgrass research was continued by the US Department of Agriculture (USDA) with a number of studies at several USDA facilities. Research in the United States was significantly increased in the second part of the 1990s and beyond, and mainly deals with switchgrass bioenergy potential.

In Canada, switchgrass is considered as a native crop of southern portions of the country, and research began in the 1990s with screening trials and continued with crop management, physiology, energy yield, and chemical composition. Nowadays, switchgrass has been adopted as an energy crop for Canada and important knowledge has been collected including growing guides as well as biomass utilization (Samson et al., 2005) based on numerous studies.

Research in Europe started in the 1990s in the United Kingdom (Christian and Riche, 2001) and continued until the end of the 1990s in the framework of two European research projects: "Switchgrass for Energy"[1] (Elbersen et al., 2004) and "Bioenergy Chains"[2] and later the OPTIMA[3] project. In the last project, switchgrass was cultivated on marginal and/or less favorable lands for conventional agriculture. It should be pointed out that at least 1,350,000 ha have been deemed as less favorable for conventional agriculture in Europe (Allen et al., 2014). Nowadays, switchgrass is considered one of the most important energy crops in Europe, especially for the production of advance biofuels, despite the fact that it is a nonnative species.

In China, switchgrass was imported in the 1990s from Japan together with other forage species (Ichizen et al., 1993, 2005), among which only switchgrass has survived. It was imported as a kind of good herbage for soil and water concentration (Ma et al., 2011). Only recently has switchgrass been considered as a candidate crop for cellulosic bioenergy feedstock in northern China and considerable research has been published since 2010. Its adaptability and productivity have been tested on arid and semiarid marginal areas of China (Yue et al., 2017). It has been estimated that the marginal land that could be used for bioenergy production in China is around 45 million ha (Zhu et al., 2014).

Besides the distribution of switchgrass on the abovementioned areas (United States, Canada, Europe, and China) a number of studies on switchgrass for bioenergy have been conducted in other areas of the globe (Parrish et al., 2012), namely, South and Central America (Argentina, Colombia, Mexico, and Venezuela), Australia, Asia (Korea, Japan, and Pakistan), and Africa (Sudan) (Fig. 3.1).

3.3 Breeding

Switchgrass is a self-incompatible and largely cross-pollinated species (Talbert et al., 1983) and there is evidence of extensive chromosome number variation, including multiple ploidy levels, as well as aneuploidy (Costich et al., 2010; Zhang et al., 2011). Currently, the existing switchgrass germplasm contains two predominant ecotypes, lowland and upland, based on morphological traits and natural habitat (Porter, 1966). Lowland ecotypes are exclusively tetraploid with genetic composition of ($2n=4\times=36$),

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[1] www.switchgrass.nl.

[2] www.cres.gr/bioenergy_chains.

[3] www.optimafp7.eu.

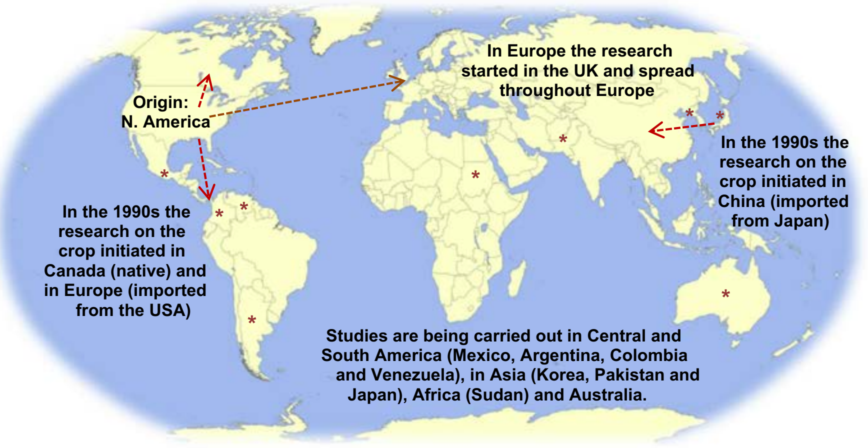

Figure 3.1 Switchgrass origin and distribution in the world.

while most of the upland are either hexaploid ($2n=6\times=54$) or octaploid ($2n=8\times=72$) (Casler, 2012). Today, switchgrass is still considered primarily an undomesticated plant with great potential for agronomic and biofuel trait improvements (Casler et al., 2015).

In the 1950s, switchgrass breeding programs in the United States and Canada were aimed at improving livestock production systems and seed yields (Eberhardt and Newell, 1959). Because switchgrass can be used as a dual-purpose (bioenergy/forage) crop (Guretzky et al., 2011), the current switchgrass breeding programs focus on: (1) increasing biomass yields and forage digestibility, (2) reducing seed dormancy, (3) improving establishment capacity, (4) improving cellulosic composition, (5) increasing tolerance to abiotic stress (cold, drought), (6) increasing resistance to diseases and pests, and (7) enhancing quality traits to improve energy production efficiency (Mitchell et al., 2008; Casler, 2012). A total of 12 breeding programs have been developed in North America (Casler, 2012).

Traditional breeding methods for perennial grasses such as switchgrass may span the course of a decade or more. A classic breeding program is divided into four phases (generation of genetic variability, selection, small-plot trials, and evaluation of improved populations), with each phase lasting approximately 5 years (Vogel and Burson, 2004; Casler, 2012). Recurrent selection has been and still is the most common breeding strategy to improve switchgrass populations (Vogel and Pedersen, 1993; Vogel and Burson, 2004). Selection can be based either on a plant's own performance or among and within families. Phenotypic recurrent selection led to the release of the only switchgrass cultivars developed with improved forage in vitro dry matter digestibility (IVDMD) (Hopkins et al., 1993; Burns et al., 2008; Casler, 2012). However, it has been reported that breeding for increased digestibility resulted in reduced lignin concentration (Casler et al., 2002) and reduced ratios of *p*-coumaric/ferulic acids (Sarath et al., 2008). Although recurrent selection was highly effective in increasing

IVDMD and seed weight and reducing seed dormancy, it did not translate into enhancing biomass yield in switchgrass (Casler et al., 2006; Burson et al., 2009).

The development of hybrid cultivars has been suggested to contribute tremendously to biomass yield potential in switchgrass (Taliaferro et al., 1999). High-parent heterosis (30%–38%) for biomass yields was observed in F1 hybrids based on crosses between lowland and upland ecotypes but not in crosses within the individual ecotypes (Martinez-Reyna and Vogel, 2008). No commercially available F1 hybrid switchgrass cultivar has been produced so far due to: (1) asynchronous flowering between the switchgrass ecotypes and (2) challenges in vegetative propagation of parental plants (Mitchell et al., 2014). Switchgrass genotypes capable of high rates of self-pollination have been discovered (Liu et al., 2014; Liu and Wu, 2012) and could be used to create inbred lines (Casler et al., 2015), which could replace the heterozygous clonal parents.

Molecular biology tools and biotechnological approaches, including molecular marker-assisted selection (MAS), quantitative trait locus (QTL) mapping, genetic engineering or gene manipulation, etc., can aid to improve or develop new switchgrass lines (Nageswara-Rao et al., 2013). In the past few years, several types of molecular markers including random amplified polymorphic DNA (Gunter et al., 1996), restriction fragment length polymorphisms (Missaoui et al., 2006), amplified fragment length polymorphisms (Todd et al., 2011), and simple sequence repeats (Zalapa et al., 2011) have been employed to analyze switchgrass genetic diversity. Complete linkage maps of two switchgrass genotypes (Serba et al., 2013) and an integrated high-density linkage map with expressed sequence tag–simple sequence repeat markers have become available, enabling efficient MAS breeding strategies (Liu et al., 2013).

Instigated by the newly available sequence data for *P. virgatum* genotype Alamo clone AP13[4] (Goodstein et al., 2012), research in switchgrass molecular genomics continues to progress rapidly. Analysis of natural variation in flowering in different ecotypes of switchgrass is necessary to clarify the molecular network of flowering time control. RNA-sequencing analysis disclosed ecotype difference in flowering time control (Tornqvist et al., 2017). Single nucleotide polymorphism markers for trait mapping for increased biomass yield (Serba et al., 2016) and the potential of genomic selection for improving the effectiveness of breeding programs in switchgrass have been revealed (Lipka et al., 2014). Twenty-seven QTLs for biomass and developmental traits have been identified, providing new targets for switchgrass manipulation using biotechnology (Lowry et al., 2015). Through breeding programs, favorable alleles of QTLs can be efficiently introduced into elite cultivars to generate new varieties with high biomass productivity and beneficial adaptations to environmental changes.

Lastly, high-throughput transformation protocols have been developed for switchgrass, with both *Agrobacterium*-mediated (Richards et al., 2001) and biolistic-mediated methods reported (Somleva et al., 2002), enabling potentially useful molecular analyses. Reducing recalcitrance of biomass is expected to have significant economic and productivity impacts in the industrial utility of switchgrass as a bioenergy feedstock. Studies have shown that lignin content could be decreased by targeting lignin biosynthesis genes with RNAi, thus improving fermentable sugar yields for

[4] http://www.phytozome.org/panicumvirgatum.php.

biofuel production (Fu et al., 2011; Xu et al., 2011). In addition, overexpression of miR156 caused an increase in overall biomass accumulation (Fu et al., 2012), and overexpression of PvMYB4 resulted in a threefold increase in hydrolysis efficiency (Shen et al., 2013). Though transgenic approaches are considered imperative for the development of switchgrass at the moment, the application of genetic engineering is seriously hindered because there is controversy regarding environmental impacts over any genetically modified crop (Nicolia et al., 2014).

3.4 Plant Physiology

3.4.1 C_4 Pathway

Switchgrass has a C_4-type photosynthetic metabolism. Based mainly on habitat preferences, switchgrass is classified into upland and lowland ecotypes, which are further subdivided into northern and southern ecotypes (Martinez-Reyna and Vogel, 2002; Casler et al., 2004). This large genetic diversity results in morphologically and physiologically different plants (i.e., tetraploid, hexaploid, and octaploid ecotypes) having specific physiological characteristic requirements in terms of ecological needs, response adaptations to environmental stresses, growth cycles, and production potential. However, in general, thanks to its deep roots, efficient stomatal control of transpiration, and relatively high photosynthetic rates (Table 3.1), switchgrass is considered a drought-tolerant species. Moreover, the radiation use efficiency (RUE) of switchgrass in one of the greatest among other traditionally cultivated crops. Kiniry et al. (2004), for example, reported a mean RUE of 4.7 g MJ^{-1} of intercepted photosynthetically active radiation for Alamo, in comparison with the 3.7 g MJ^{-1} reported for maize in Texas. Even though both species have a C_4 photosynthesis pathway, the high leaf area index and the low light extinction coefficient of switchgrass may render it more radiation use efficient (Kiniry et al., 2011). Also, octaploid cultivars usually show higher photosynthetic rates than tetraploid cultivars (Zegada-Lizarazu et al., 2012). Such higher leaf gas exchange capacity is related to a greater activity of ribulose-1,5-bisphosphate carboxylase, phosphoenolpyruvate carboxylase, NAD-malic enzymes, concentration of biochemical constituents, and smaller cell size (Warner et al., 1987). According to Wullschleger et al. (1996), more than the ploidy level, the main determinant factors for higher or lower photosynthetic rates in either switchgrass type are the ontogenic changes of the plant along the growing season and the availability of soil resources (mainly water).

3.4.2 Water and Nutrient Efficiency

Switchgrass has a high WUE attributed to its C_4 cycle and therefore to its efficient photosynthetic pathway (Table 3.1). At the same time, the high WUE and water uptake capacity of switchgrass seems to be related more to its root length density than to its distribution along the soil profile (Monti and Zatta, 2009). Thus water may passively move into switchgrass roots in response to water potential gradients, rather than actively pumping solutes to create an osmotic gradient in the cell-to-cell pathway as

Table 3.1 Some physiological characteristics of lowland and upland switchgrass varieties

Cultivar	Photosynthesis ($\mathrm{mmol\,m^{-2}\,s^{-1}}$)	Transpiration ($\mathrm{mmol\,m^{-2}\,s^{-1}}$)	Stomatal conductance ($\mathrm{mol\,m^{-2}\,s^{-1}}$)	Instantaneous water use efficiency ($\mathrm{mmol\,m^{-2}\,s^{-1}}$)	Nitrogen use efficiency
Lowland					
Alamo	30.5[a,b,c]	8.2[a,b,c]	0.23[a,b,c]	3.6[a,b,c]	47.0[d]
Kanlow	22.0[e]	2.3[e]	0.15[e,f]	9.5[e]	–
NC-116	33.3[a,b,c]	–	–	–	–
NC-216	32.1[a,b,c]	–	–	–	–
PMT-279	34.3[a,b,c]	–	–	–	–
PMT-785	29.9[a,b,c]	–	–	–	–
NJ-50	–	–	–	–	33.0[g]
Upland					
Pathfinder	9.7[a,b,c]	2.2[a,b,c]	–	4.5[a,b,c]	33.8[h]
Sunburst	8.9[a,b,c]	2.4[a,b,c]	–	3.9[a,b,c]	15.5[i]
Cave-in-Rock	23.5[a,b,c]	3.1[a,b,c]	–	4.0[a,b,c]	23.2[j]
Blackwell	10.8[a,b,c]	3.0[a,b,c]	–	4.4[a,b,c]	4.9[i]
Dacotah	8.5[a,b,c]	2.2[a,b,c]	–	3.9[a,b,c]	–
Forestburg	9.9[a,b,c]	2.5[a,b,c]	–	4.4[a,b,c]	–
Nebraska 28	10.3[a,b,c]	1.8[a,b,c]	–	5.7[a,b,c]	–
Caddo	25.4[a,b,c]	–	–	–	–
Shelter	28.4[a,b,c]	–	–	–	–
Contrast					
Lowland	30.4	5.2	0.19	6.5	40.0
Upland	15.1	2.5	–	4.4	19.4

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[a] Wullschleger et al. (1996).
[b] Sanderson et al. (1996).
[c] Ma et al. (2011).
[d] Muir et al. (2001).
[e] Kim et al. (2016).
[f] Cordero and Osborne (2017).
[g] Staley et al. (1991).
[h] Obour et al. (2017).
[i] Owens et al. (2013).
[j] Sadeghpour et al. (2014).

the wetting front moves downward (Zegada-Lizarazu et al., 2012). Moreover, the deep root systems of switchgrass may facilitate access to deep, moist soil layers, which could significantly contribute to enhancing the transpiration efficiency and/or adjust the water needs of the plant. Stout et al. (1998) indicated that soil characteristics such as water-holding capacity are the major determinants for variable WUE in switchgrass under different rainfall regimes. Also the variable WUE of switchgrass is often related to plant ecomorphological characteristics. We showed, for example, that WUE of lowland ecotypes is higher than that of upland ecotypes (Zegada-Lizarazu et al., 2012). In the lowland ecotypes with taller and thicker stems, longer bluish-green leaves, and higher biomass yield potential (Parrish and Fike, 2005; Fike et al., 2006) the WUE averaged 25.6 kg ha^{-1} mm^{-1}, whereas in upland ecotypes the WUE averaged only 16.2 kg ha^{-1} mm^{-1}.

In general, the nutrient requirements of switchgrass are considerably lower than those of conventional annual crops, therefore less input is required and important environmental impacts could be avoided, which makes switchgrass a very attractive energy crop. However, even though the nitrogen use efficiency (NUE) of switchgrass is usually higher than annual crops, it has been reported inefficient in NUE with higher N fertilization doses. Obour et al. (2017), for example, reported an NUE decrease from 46 kg^{-1} N applied at 45 kg N ha^{-1} to 22 kg kg^{-1} N applied when fertilized with 180 kg N ha^{-1}. However, Lemus et al. (2008) indicated an average biomass yield increment of about only 9 kg N kg^{-1} year^{-1} with increasing fertilization rates from 90 to 270 kg N ha^{-1}. In addition, the rhizomatous root system of switchgrass allows nutrients to be cycled annually from the canopy to the rhizomes at senescence and vice versa during resprouting, thus reducing the need for fertilization amendments and therefore increasing NUE (Vogel, 2004a,b; Lemus et al., 2008, 2009). It was estimated, for example, that half of the N reserves accumulated in the plant canopy could be translocated to the roots at plant senescence (Garten et al., 2010). Moreover, phosphorus, potassium, and other nutrients are also recycled in a switchgrass stand (McLaughlin and Kszos, 2005; Lemus et al., 2009), but instead of being remobilized within the plant organs (i.e., from canopy to roots) these nutrients are mainly leached from senesced plant tissues to the soil. The relatively high NUE of switchgrass could be in part also attributed to its symbiotic associations with mycorrhiza. Studies have identified some strains of *Flavobacterium nitrogenifigens* sp. nov. in the rhizosphere of switchgrass (Xu, 2014; Kämpfer et al., 2015). Moreover, the possibility of inoculating switchgrass with endophytes capable of fixating N was reported by Ker et al. (2014) with encouraging results.

3.4.3 Water Stress

The effects of drought stress in switchgrass are limited thanks to its high leaf area index, increased leaf/tiller index, leaf rolling, pubescent and waxy leaves, changes in leaf orientation, leaf senescence, abscisic induction of stomata control and transpiration, osmotic adjustment, and the capacity to develop deep roots (Sanderson et al., 1997a,b; Awada et al., 2002; Stroup et al., 2003; Zhang et al., 2011; Liu et al., 2015). Moreover, Liu et al. (2015) considered that physiological traits are closely related to short-term drought tolerance in switchgrass. Likewise, the C_4 physiology of switchgrass may allow the crop to develop a laterally and vertically well-expanded root system able to explore a large volume of soil to acquire the soil resources efficiently (i.e., water, nutrients). Such large soil exploration capacity may allow switchgrass to maintain high photosynthetic and therefore growth rates even under variable levels of drought stress.

In general, upland ecotypes are considered better adapted to drought conditions than lowland ecotypes due to more pubescent leaves (Hultquist et al., 1996; Martinez-Reyna et al., 2001). However, there are several studies that did not find systematic differences in response to drought between upland and lowland ecotypes. Barney et al. (2009), for example, reported similar biomass and morphophysiological reductions in both ecotypes when exposed to severe drought conditions ranging from −4.0 to −11.0 MPa. In the same line, Stroup et al. (2003) did not find any significant effect of mild drought (−1 MPa) on the biomass production of both ecotypes. Moreover, a study has demonstrated that either lowland or upland ecotypes could belong to polymerase chain reaction clustered groups with higher or lower tolerance to drought depending on their leaf gas change capacity, water status, WUE, and electrolyte leakage (Liu et al., 2015). However, in general, variations in drought tolerance are indicated to be more a consequence of reduced stomatal conductance, osmotic adjustment, and remobilization of leaf components, mainly proteins (Heckathon and Delucia, 1994; Byrd and May 2000), than ploidy level and/or photosynthetic capacity.

3.5 Plant Agronomy

Switchgrass management as a bioenergy crop is relatively new. When it was first selected as a promising energy crop it was assumed that its management should be similar to forage management (Sanderson et al., 2006). Thereafter, it was found that switchgrass management should be adjusted in terms of high efficiency of soil management and nitrogen fertilizers to minimize external energy inputs and harvest management to maximize the lignocellulose yields. In this section, crop establishment (seedbed preparation and sowing), available varieties, needed fertilization, water needs, crops yields, weed control, and harvesting and storage will be discussed.

3.5.1 Seedbed Preparation, Sowing, and Seed Dormancy

Switchgrass can grow under variable soil conditions ranging from sand to clay loam (Vogel, 2004a,b), although it grows best on well-drained fertile soils. Nowadays, switchgrass is mainly investigated as an energy crop, which means that it will be cultivated in areas that are not appropriate for food and feed crop production such as low fertility and/or marginal areas. Although switchgrass seeds germinate best in soils with pH between 6 and 8, the seedlings can tolerate less favorable pH values varying from 3.7 to 7.6 (Vogel, 2004a,b; Parrish and Fike, 2005; Casler et al., 2004). Soil samples should be taken prior to crop establishment to determine the soil nutrient status.

Switchgrass has been successfully established under various tillage practices (Casler et al., 2004). A firm seedbed is recommended for proper seed placement regardless of planting method since switchgrass is planted at a shallow depth. Planting switchgrass using conventional tillage methods is a common practice for effective establishment. Conventional tillage can control or reduce cool-season weed populations and reduce residue from previous cropping systems. Conventional tillage should be avoided on fields with steep slopes because of the risk of soil erosion. For bioenergy purposes, both pre- and postemergence herbicides are critical under no-tillage practices to control or reduce weed populations during the establishment year.

Proper planning is a key factor for successful establishment of the crop. The main factors that should be considered for successful crop establishment are: seedling depth, soil texture, soil moisture, and soil temperature (Parrish and Fike, 2005). Moreover, the selection of the proper variety having a high percentage of pure live seed (PLS) should also be considered for successful establishment. The recommended planting depths for switchgrass could be varied from 0.2 to 2 cm (Moser and Vogel, 1995), although seedling depths of 3 cm have been recommended on coarse-textured soils (Parrish and Fike, 2005). According to Berti and Johnson (2013) the soil depth should be no deeper than 13 mm.

At sowing, high germination rates could be ensured if the soil temperature is around or higher than 20°C (Hsu and Nielson, 1986a,b). According to Dierberger (1991) the optimal germination of several switchgrass cultivars was found to be between 27 and 30°C. It is reported that germination tolerance to temperature of switchgrass seeds could be varied among the varieties (Seepaul et al., 2011).

The recommended seeding rates for switchgrass are 200–400 PLS m^{-2}. A lower seeding rate (107 PLS m^{-2}) gave adequate stands for conservation plantings (Vogel, 1987) in fields with excellent weed control. According to West and Kincer (2011), applied seeding rates varied from 4.48 to 11.20 kg ha^{-1} in the southeast United States, which resulted in similar biomass yields in the postestablishment years. It is recommended that before sowing, germination tests are to be carried out for the selected variety so that the appropriate seeding rate can be adjusted based on the test results. The average seed weight is 850 seeds g^{-1} (Jensen et al., 2007). The seed weight varies not only among the different switchgrass varieties but also within the same variety. Although heavier seeds had higher germination capacity and higher growth rate (Aiken and Springer, 1995; Green and Bransby, 1995) compared to the lighter seeds, no growth differences could be detected 8 to 10 weeks after emergence (Smart and Moser, 1999).

The seeds that are unable to germinate even if they have been sown in suitable soil conditions are characterized by seed dormancy. Seed dormancy can reduce seedling vigor and establishment. It is reported that seed dormancy is caused by structures that surround the embryo and mechanisms within the embryo (Knapp, 2000). When genetic selection for low seed dormancy had been done in varieties with lowland ecotype, the result was lower overall primary dormancy (Sanderson et al., 1996). Primary dormancy of switchgrass seed can be broken by an after-ripening period or by cold stratification (Moser and Vogel, 1995). Seeds that are stored for 3 or more years at room temperature may have poor seedling vigor and reduced establishment

(Vogel, 2002). Several seed treatments have been investigated for their ability to increase switchgrass germination and establishment.

In the northern United States, it was recommended that switchgrass planting should be done in the period extending from 3 weeks before until 3 weeks after corn planting (Vassey et al., 1985). In the same work it has been reported that when switchgrass was planted in the period from mid-April to early May, higher yields were recorded at the establishment year compared with later planting dates. Similar findings were reported in other studies conducted in mid-latitude areas of the United States (Hsu and Nielson, 1986a,b) when planting was done from late April to mid-May. In Nebraska, it has been reported (Smart and Moser, 1997) that higher biomass yields were recorded at the establishment year when the planting was done as early as March compared to later plantings of April and May. In the switchgrass trials that had been conducted in southern Europe the sowing dates varied from late April to mid-May.

A grass seedling is considered fully established when adventitious roots are formed, are able to overwinter, and can survive the following season (Hyder et al., 1971; Whalley et al., 1996). Under favorable environmental conditions, adventitious root development is initiated 2–4 weeks after emergence (Moser, 2000). The most important parameter for adventitious root development is adequate soil surface moisture (Newman and Moser, 1998). The adventitious roots characterized by higher water uptake and nutrient absorption compete with the primary root system (Moser, 2000; Newman and Moser, 1998). At least one adventitious root should be developed by the three-leaf emergence stage. In Fig. 3.2, switchgrass seedlings (variety Alamo) are presented 2, 3, and 5 weeks after sowing (OPTIMA project).

Switchgrass seedlings must develop two or more tillers to survive winter (O'Brien et al., 2008). Under normal weather conditions and proper agronomic management, switchgrass can achieve more than 50% of full yield potential during the establishment year (Schmer et al., 2006). Harvesting switchgrass in the establishment year reduces farm-gate production costs and improves economic returns (Perrin et al., 2008). Establishment year stands with at least 20 seedlings m^{-2} and minimal weed pressure are considered to be fully adequate for bioenergy purposes. Switchgrass has the ability to produce similar biomass yield under different seedling densities as a result of compensatory responses to tiller number and sizes (Sanderson and Reed, 2000).

Figure 3.2 Switchgrass seedlings of the lowland variety Alamo in a field trial located on a marginal area in central Greece; sowing took place on May 11, 2012.
From CRES/OPTIMA Project.

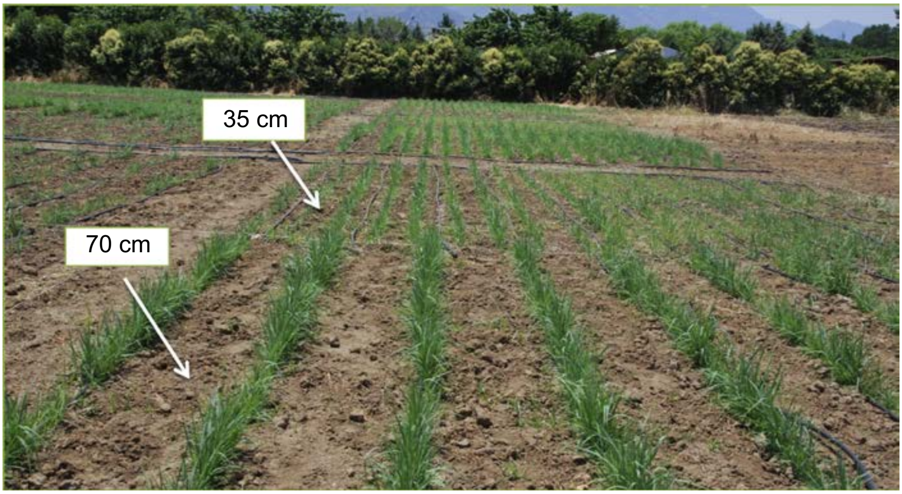

Figure 3.3 Two distances between the rows; 35 and 70 cm (cv. Alamo, June 25, 2012). From CRES/OPTIMA Project.

Row distance is an important factor in determining switchgrass productivity. A narrow row distance will accelerate canopy closure in spring, which will increase total light interception over the season and thus crop productivity. Earlier crop closure will contribute significantly to weed competition reduction. At high tiller densities, self-thinking of the stand is recorded. Alexopoulou et al. (2008) reported that when switchgrass was planted in very narrow rows (15 cm) a quite early crop closure was achieved, but lodging problems were recorded at the establishment year that were more severe in the plots of the upland varieties than in the plots of the lowland varieties as a result of higher tiller density combined with smaller tiller diameter.

Several row-spacing studies have been conducted in switchgrass. Ocumpaugh et al. (2003) compared row spacing of 15, 30, and 50 cm and found that in drought conditions wider-spaced treatments had higher yields. Bransby et al. (2005) found that in Alabama, wide-spaced (80 cm) stands yielded more than narrow-spaced stands (20 cm) after the first year. Yield increase was especially evident several years after establishment. In the first EU project (Switchgrass for Energy) the distances between the rows were too narrow (15 cm), in the Bioenergy Chains project larger rows were tested (40 cm), while in the OPTIMA project even larger distances were tested (70 cm). In Fig. 3.3, plots with two distances between the rows are presented: 35 and 70 cm (OPTIMA project).

3.5.2 Varieties

Switchgrass is a highly polymorphic and largely self-incompatible crop (Talbert et al., 1983; Taliaferro and Hopkins, 1997). The basic chromosome number of switchgrass is x = 9. The ploidy levels of switchgrass vary from diploid ($2n=18$) to duodecaploid ($2n=108$) (Hultquist et al., 1996; McMillan, 1959; Nielsen, 1944; Riley and Vogel, 1982). In Table 3.2 the ploidy levels for switchgrass varieties are given based on the literature. Seed weight is generally larger for octaploid than for tetraploid varieties (Table 3.2).

Table 3.2 Switchgrass varieties (lowland or upland), ploidy level, origin, maturity, seed weight, and adaptation

Variety	Ploidy level	Origin	Maturity	Seed weight (wt, mg)	Adaptation
Lowland					
Alamo[a,b,c]	Tetraploid	South Texas 27°	Very late	94	Up to 2.5 m high, coarse, late flowering, rainfall >630 mm
Kanlow[a,b,c]	Tetraploid	Central Oklahoma ~34.8°	Very late	85	Tall, coarse, poorly drained soils, wide adaptation, no drought tolerance, slow establishment
NL 93-1[d]		36°–40°, 223 days to heading		121	Developed at Oklahoma State University (OSU) by Taliaferro and Hopkins
NL 93-2[d]				89	
PMT-279[b,c]	Tetraploid	South Texas 29° 26°–30°			
SL 93-2[d]	Tetraploid	26°–30°		87	Developed at OSU by Taliaferro and Hopkins; derived from Alamo and relative germplasms
SL 93-3[d]	Tetraploid			100	
SL 94-1[d]	Tetraploid			91	
Wabasso[c]	Tetraploid	Southern Florida ~27°	Very late		Increased vegetatively
9005438		Wyoming	Late	177	Southern, light green, leafy, tall, high production
Pangburn[c]	Tetraploid	Arkansas		96	
Upland					
Blackwell[a,b,c]	Octaploid	Northern Oklahoma ~36.7°	Mid/late	142	Disease resistance, heavy stems, medium height, 380–760 mm, appropriate also for lowland sandy areas

Continued

Table 3.2 Switchgrass varieties (lowland or upland), ploidy level, origin, maturity, seed weight, and adaptation—cont'd

Variety	Ploidy level	Origin	Maturity	Seed weight (wt, mg)	Adaptation
Carthage[a,e]		North Carolina 26°	Late	148	
Caddo[a,b,c,f]	Octaploid	Northern Oklahoma ~34.8°	Late	159	Plant tall, robust, high seed production, and outstanding forage yield under irrigation. Excellent seedling vigor, resistant to leaf rust
Cave-in-Rock (CIR)[a,b,c,g]	Octaploid	Southern Illinois ~ 38.8°	Late	166	Medium to coarse. Resistance to zonate leaf-spot and rust, good in humid conditions. 1.5 m tall, well-drained soils, moderate seedling vigor, coarser than Pathfinder and Blackwell
Dacotah[a,b]	Tetraploid	North Dakota ~ 46.3°	Very early	148	Adequate forage and higher latitude of adaptation, short, early maturity
Forestburg[a,b]	Tetraploid	South Dakota ~44.2°	Early	146	Forage yield high, very winter hardy, persistent, early
Nebraska 28[a,c]		Northern Nebraska ~42.6°	Early/mid	162	Well adapted to diverse soils. Susceptible to rust in areas
NU 94-2[d]		36°–40°, 210 days to heading		173	Developed at OSU by Taliaferro and Hopkins
Pathfinder[a,b,c,h]	Octaploid	Nebraska/Kansas ~ 39.9°	Mid/late	187	Good establishment, vigorous, winter hardy, leafy and rust resistant

REAP 921	Tetraploid	South Nebraska	Early/mid	90	Resistance to lodging in Canada, small seeded with slow establishment
Shawnee[i]	Octaploid	South Illinois ~38.8°	Mid/late		CIR in base, high in vitro dry matter digestibility (IVDMD)
Shelter[a,b,c]	Octaploid	West Virginia ~41.7°	Mid	179	Upright, stiff thicker stems, fewer leaves, lower seedling vigor, 7–10 days earlier than Blackwell
SU 94-1[d]		23–34 South Central Oklahoma		183	Developed at OSU by Taliaferro and Hopkins
Summer[b,c]	Tetraploid	South Nebraska ~40.8°	Late/mid	113.5	Mostly rust resistant, tall for north, upright, coarse leaves, high yield of forage and seed
Sunburst[a,c]		South Dakota ~43.4°	Mid	198	Winter hardy, leafy, and heavy seeded, good seedling vigor
Trailblazer[a,b,c,i]		Nebraska ~40°	Mid	185	High IVDMD compared to Pathfinder
9005439		Wheatland Wyoming		183	Northern, tall, leafy, dark green, disease resistant

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[a] Alderson and Sharp (1993).
[b] Gunter et al. (1996).
[c] Hopkins et al. (1996).
[d] Taliaferro and Hopkins (1997).
[e] Stout et al. (1998).
[f] Hein (1958).
[g] George and Reigh (1987).
[h] Newell (1968).
[i] Vogel et al. (1981).

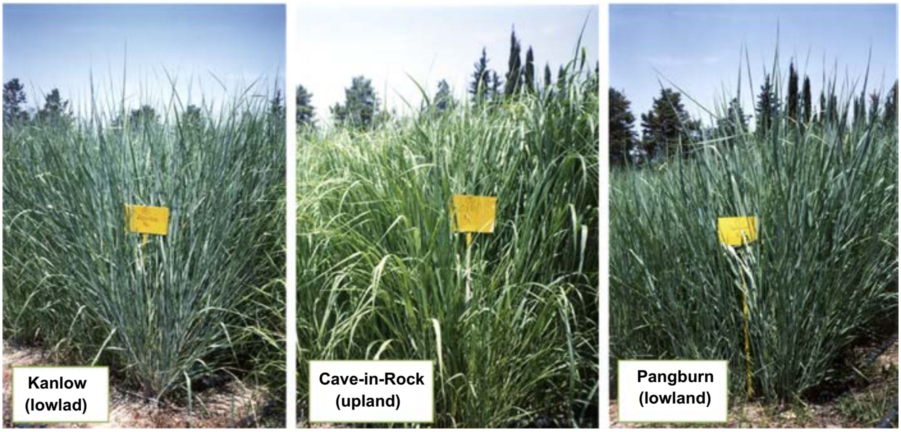

Figure 3.4 View of the three switchgrass varieties: two lowland (Kanlow and Pangburn) and one upland (Cave-in-Rock) in the third growing period (July 13, 2000).
From CRES, Switchgrass for Energy—www.switchgrass.nl.

Figure 3.5 View of the switchgrass trial at the second growing period (the trial was established in 1998); the plots with the lowland varieties are those in dark green (dark gray in print versions) color, while the upland varieties are in light green (gray in print versions).

Historically, based on the morphology and the habitat of natural switchgrass populations, two main ecotypes have been classified: upland and lowland (Porter, 1966). Lowland ecotypes are taller than upland ecotypes and they have longer bluish-green leaves and longer ligules (Figs. 3.4 and 3.5). The upland ecotypes are better adapted to colder and drier habitats, while the lowland ecotypes tend to thrive in warmer and wetter habitats (Porter, 1966). With the same ecotype (lowland and upland) the varieties can be further distinguished to northern and southern (Moser and Vogel, 1995). It has been reported (Martinez-Reyna and Vogel, 2002) that with lowland and upland varieties with the same chromosome number, viable seed could be produced and the F1 hybrids gave higher biomass yields compared to their parents (Vogel and Mitchell, 2008).

Lowland varieties have higher maximum single leaf photosynthesis compared to upland varieties (Wullschleger et al., 1996) but this trend could be reserved after a drought period. The majority of the lowland varieties are tetraploid, while the upland varieties are octaploid (Table 3.2). In the southern United States, lowland varieties such as Alamo and Kanlow generally yield more dry matter than upland varieties (Parrish et al., 1997). Unfortunately, it seems that northern ecotypes are mostly of the upland type. New lowland and upland varieties are being developed specifically for biomass production for southern and northern regions (Taliaferro and Hopkins, 1997). Wullschleger et al. (2010) reported that the lowland ecotypes were able to outperform the upland ecotypes ($12.0 \pm 5.9\,\mathrm{Mg\,ha^{-1}}$ vs. $8.7 \pm 4.2\,\mathrm{Mg\,ha^{-1}}$) in a study carried out in 39 sites and in 17 states of United States.

The main factors that determine the adaptation area of each variety are: length of daylight (photoperiod), precipitation, and humidity (Moser and Vogel, 1995). Switchgrass is sensitive to photoperiod and short days will induce flowering in early summer. When different varieties are grown in the same site, northern ecotypes will remain shorter, flower earlier, and mature earlier than southern ecotypes. Also production of biomass will be considerably less compared to southern types. Samson et al. (1997) compared dry yields of two upland varieties [Cave-in-Rock (CIR) and Dacotah] that had different lengths of maturity and found that the one with the shorter period (100 days for Dacotah and 135 for CIR) was the one with the lowest yields (6 vs. $12\,\mathrm{Mg\,ha^{-1}}$). Varieties with the same length of vegetative growth produce the same number of leaves before panicle appearance (Van Esbroeck et al., 1997). When varieties with southern ecotypes moved to the north they often failed to produce seeds at the end of the growing period and this could prevent the winter hardening of the crop and lead to a poor winter survival (Moser and Vogel, 1995). Furthermore, the harvesting material would have higher moisture content as well as nutrient content because the nutrient had not been managed to translocate to the below-grown parts (Sanderson and Wolf, 1995), while the regrowth of the following spring could be negatively affected.

The research studies that had been carried out in Europe indicated that the lowland varieties were more productive than the upland varieties. Monti et al. (2008) reported mean dry biomass yields (4 years) of 14.9 for the lowland and $11.7\,\mathrm{Mg\,ha^{-1}}$ for the upland. Alexopoulou et al. (2008) also reported a superiority of lowland over upland varieties based on field trials conducted for 5 years in Greece and Italy. When the previous research on Greece was carried out for 17 years the same superiority of lowland over upland (12.4 vs. $11.4\,\mathrm{Mg\,ha^{-1}}$) was confirmed (Alexopoulou et al., 2017) but it was smaller compared to the 5-year trial. The opposite findings had been published from another study that had been carried out in Italy for a shorter period (4 years), where the upland had superior productivity over the lowland (Monti et al., 2008). In Fig. 3.6, unpublished data are presented from a long-term switchgrass trial (1998–2014) with 10 varieties (six upland and four lowland) that had been established in Greece by CRES in the framework of the Switchgrass for Energy project.

3.5.3 Fertilization

Switchgrass tolerates acid and infertile soil conditions that could not be used by cool-season grasses, although it grows best in soils with neutral pH (Jung et al., 1988). Moser and Vogel (1995) reported that it tolerates soil with pH from 4.9 to 7. In another study, Porter (1966) reported switchgrass growing on alkali soils (pH 8.9 to 9.1).

The optimum nitrogen fertilization for switchgrass, when cultivated as a bioenergy crop, varies greatly according to the environmental conditions, the N availability in soil, and the harvest frequency and management (Lemus et al., 2009; Mulkey et al., 2006; Thomason et al., 2004; Brejda, 2000). Mitchell and Anderson (2008) stated that nitrogen fertilization is not recommended during the establishment year because

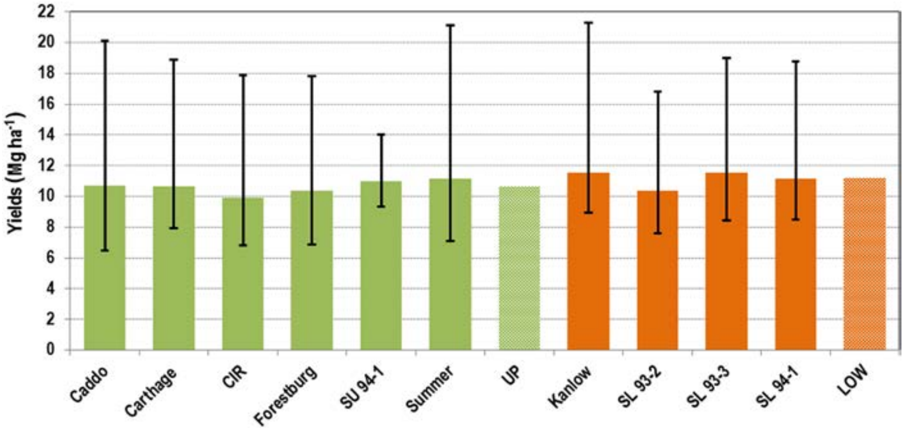

Figure 3.6 Mean dry yields (Mg ha^{-1}) for 10 switchgrass varieties (six upland and four lowland) for a period of 17 years (1998–2014). The vertical bars present the max and min yields among the years; the majority of the varieties [apart from Cave-in-Rock (CIR), Kanlow, and SL 94-1] produced the celling yields in year 2 and the rest in the following year.

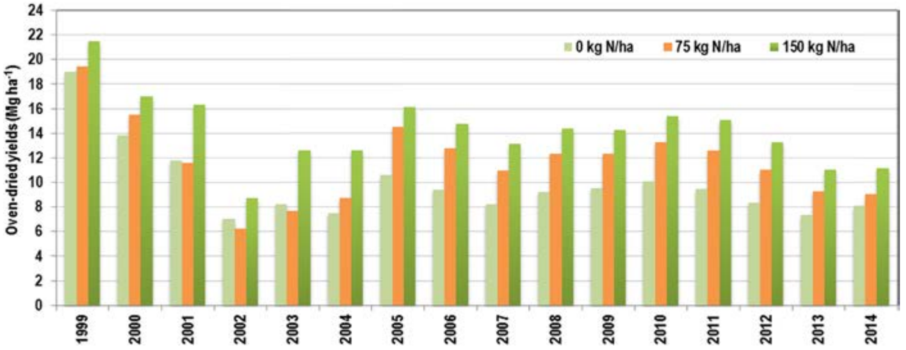

Figure 3.7 Effect of nitrogen fertilization on yields for a period of 16 years as a mean of five switchgrass varieties [two upland varieties: Blackwell and Cave-in-Rock (CIR); three lowland varieties: Alamo, Kanlow, Pangburn].

it encourages weed growth and increases the competition between switchgrass seedlings and weeds, the establishment cost, and finally the economic risk. It is reported that in areas (western Europe) where switchgrass was harvested quite late in winter (after a killing frost) the yield response to nitrogen fertilization was quite small even if the crop was grown for many years with no nitrogen fertilization (Sanderson et al., 2012). In a long-term study (17 years) on switchgrass conducted on a marginal area in Greece it was found that when the nitrogen rates were increased from 0 to 75 and 150 kg N ha^{-1} the yields were also increased but this increase was significant from the sixth growing period and thereafter (Alexopoulou et al., 2017, Fig. 3.7).

According to Moser and Vogel (1995), switchgrass makes good use of organic nitrogen since the highest growth rates occur when the mineralization of organic N is highest. The high rate of mineralization and uptake of switchgrass may contribute to lodging, which has been recorded in several sites in Europe. It has been reported (Alexopoulou et al., 2017) that the lodging problems were higher in the plots that were highly fertilized (150 kg N ha^{-1}) compared to the plots that received only half fertilization (75 kg N ha^{-1}). Heavy soils with high N content did not show any response to the additional nitrogen application for several years (Christian and Elbersen, 1998).

The harvest management of the plantation could play an important role in the effect of nitrogen fertilization of the crop. When the crop is harvested quite late in the season (after a killing frost) the harvested material has less nitrogen content (Vogel et al., 2002), since some nutrients have already been translocated to underground tissue and thus less nitrogen application will be needed in the following year. Turhollow (1991) estimated that switchgrass for biomass production requires only 50 kg N ha^{-1}.

Less research has been done relative to P and K fertilization of switchgrass for biomass or forage. Recommendations for P and K application are based on soil test levels and soil characteristics (Lemus et al., 2008). There was no response of switchgrass to P application at two locations in Texas, USA, over a 3- or 7-year period (Muir et al., 2001). Switchgrass production increased when P and N or P, K, and N were applied together with lime compared to N alone on five different soils in Louisiana, USA (Taylor and Allinson, 1982); however, the authors speculated that response to P fertilization would be limited without N. Most studies on phosphate fertilization report that switchgrass does not show a response to P fertilization even if soil values are low (Jung et al., 1990, 1988; Ocumpaugh et al., 2003).

3.5.4 Irrigation

Switchgrass demonstrates broad tolerance to soil moisture availability by germinating, establishing, and reproducing under both moisture deficit and flooded conditions. Environmental variability throughout its vast native range has likely led to this adaptive tolerance, which appears greater in current cultivars than in wild types of a few generations ago. However, there may be a fitness trade-off for broad environmental tolerance (e.g., reduced competitive ability), as switchgrass is often difficult to establish in weedy agronomic fields. Barney et al. (2009) reported that much of eastern North America is highly suitable for switchgrass production, while areas with a Mediterranean climate such as California are unsuitable without irrigation.

Switchgrass varieties differ in water requirements with upland varieties growing better under moderate soil moisture, whereas lowland types performed best under high soil moisture (Porter, 1966). Switchgrass has been shown to have high WUE (Wagle and Kakani, 2014) and mature switchgrass has shown high productivity under moderate drought (Eichelmann et al., 2015). Some studies have shown switchgrass can survive extreme drought, but significant reduction of aboveground biomass occurs under drought (Barney et al., 2009; Knapp, 1984). It is important to assess the impact of large-scale switchgrass production on the local and regional water budget and consequences for switchgrass productivity to make decisions about its sustainability.

In Fig. 3.8 the effect of irrigation on switchgrass when cultivated in Greece is presented. The switchgrass plants (cv. Alamo) in the plots that did not receive any

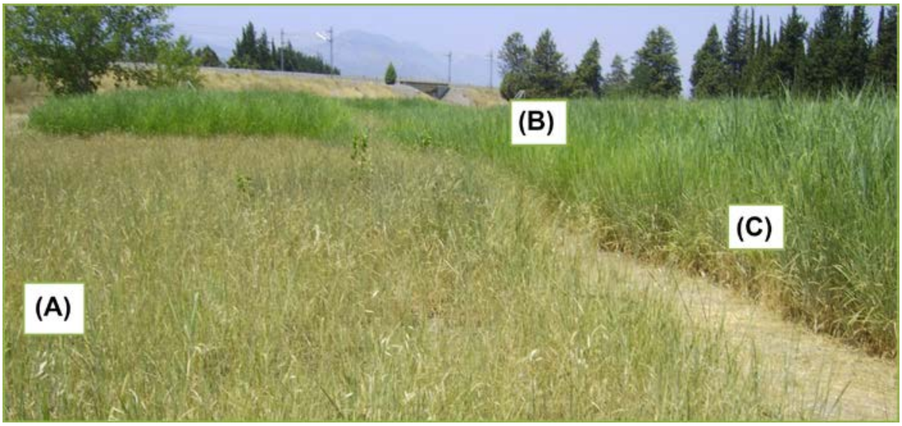

Figure 3.8 Effect of irrigation on switchgrass growth: (A) nonirrigated, (B) 50% of potential evapor transpiration (PET), and (C) 100% of PET; cv. Alamo, eighth growing period (mid-July).

irrigation, apart from rainfall, were quite shorter than the irrigated plants with a smaller number of tillers per plant, while the majority of the tillers did not develop panicles (Bioenergy Chains project). The irrigation effect on growth and yields was more profound in those growing seasons that the rainfalls were quite rate during the hot summer period.

3.5.5 Weed and Pest Control at the Establishment Year

Weed competition is a major reason for switchgrass failure during establishment. Acceptable switchgrass production can be delayed by 1 or 2 years by weed completion and poor stand establishment (Schmer et al., 2006). The most common weeds in establishing warm-season grasses such as switchgrass are annual grasses such as crabgrass, green foxtail, yellow foxtail, autumn panicum, and barnyardgrass. The recommended practice of controlling weeds in fields planted with switchgrass is the use of preemergent herbicides, in particular for annual grass control. Nonselective herbicides, such as glyphosate, are effective in weed control before switchgrass emergence especially under no-till plantings.

Atrazine has been reported as an effective herbicide during switchgrass establishment, controlling mainly cool-season annual grasses and broadleaf weeds (Vassey et al., 1985; Martin et al., 1982). Quinclorac is another effective herbicide in switchgrass establishment that controls successfully the warm-season annual grasses such as giant foxtail, green foxtail, yellow foxtail, and barnyardgrass along with a limited number of broadleaf species (Masters and Sheley, 2001). Switchgrass treated with a preemergence combination of Quinclorac and atrazine had higher biomass yields and comparable switchgrass stand frequencies compared with switchgrass treated with atrazine or Quinclorac alone, and both herbicides were equally effective on lowland and upland ecotypes (Mitchell et al., 2010a,b). The use of 2,4-D is cost effective for broadleaf weed control when applied postemergence at the four- or five-leaf stage. Broadleaf weed control using mechanical treatment (moving) can be successful when broadleaf weeds are taller than switchgrass and the moving application can be done to minimize switchgrass leaf loss (Elbersen et al., 2004). Hardly any weed control is needed in a well-established switchgrass stand the years after establishment.

3.6 Harvesting

Selection of optimal harvest and postharvest management practices for switchgrass is strongly dependent on end use (Vogel et al., 2011). Since initially switchgrass had been selected as a forage crop there is a research history of harvesting and preserving hay for livestock. Although switchgrass management as an energy crop is relatively new, harvesting and baling could be done with commercially available haying equipment after some modifications (Mitchell et al., 2008). It is recommended (Vogel et al., 2011) that the cutting height for switchgrass should be higher than 10 cm, which keeps the windrows elevated above the soil surface to facilitate air movement and more rapid drying to less than 20% moisture content prior to baling. The harvested material can be balled in large bales, round or rectangular, for storage and transportation (Vogel et al., 2011). The round bales are suggested when switchgrass is going to be stored outside since they tend to have fewer storage losses compared to rectangular bales. The rectangular bales are easier to handle and load onto trucks for transport without road width restrictions (Vogel et al., 2011). In Fig. 3.9 the harvesting and baling (round or square bales) that had been carried out by the University of Bologna in the framework of the Bioenergy Chains project are presented.

3.6.1 Harvesting Time

Most research studies agreed that a single annual harvest could assure optimized biomass and energy inputs, as well as the maintenance of switchgrass stands. Switchgrass harvesting that took place two or three times each year (Newell and Keim, 1947) resulted in greater stand reductions. Switchgrass harvested once at anthesis in Nebraska and Iowa had greater biomass than areas harvested twice (Vogel et al., 2002). The time of the single harvest varies among the reported studies. Biomass was maximized with a single harvest during anthesis and yields ranged from 10.5 to 12.6 $\text{Mg ha}^{-1}\,\text{yr}^{-1}$ with no stand reduction (Vogel et al., 2002). Sanderson et al. (1999) harvested several switchgrass strains once or twice per growing season from multiple environments and concluded that a single harvest in the fall maximized biomass and maintained stands.

Proper harvest timing, cutting height, and adequate N fertility are important management practices required to maximize yield and ensure persistent switchgrass stands (Vogel et al., 2011). As previously mentioned, research on harvesting time indicates that a single harvest at postanthesis maximizes yields, but harvesting after a killing frost ensures stand persistence and productivity, especially during drought (Vogel et al., 2011). Moreover, harvesting after a killing frost minimizes nutrient removal, especially N (Hancock, 2009). Vogel et al. (2011) reported that switchgrass should not

Figure 3.9 Harvesting of switchgrass in Italy (Agricultural University of Bologna, Bioenergy Chains project).

Figure 3.10 View of switchgrass trial in mid-December 2014 (second growing period of the trial).

be harvested within 6 weeks of the first killing frost or at a tiller height less than 10 cm to ensure carbohydrate translocation to plant crowns for setting new tiller buds and maintaining stand productivity.

In the field trials that had been conducted in Europe a single harvest was applied a few weeks after the first killing frost of the cold season. In Fig. 3.10 a switchgrass trial a few days after the first killing frost of the winter is presented. As shown the plantation looks quite dry (middle of December) but harvesting took place 4 weeks later (middle of January) so that nutrients removal to the rhizomes could be completed and the moisture content of the crop could be as low as possible.

In general, delaying harvest until after a killing frost reduces yield but ensures stand productivity and persistence, especially during drought, and reduces N fertilizer requirements for the following year by about 30% (Vogel et al., 2011; Mitchell et al., 2010a,b). Postfrost harvests allow N and other nutrients to be translocated into roots for storage during winter and used for new growth the following spring, but will reduce the amount of snow captured during winter and will limit winter wildlife habitat value (Mitchell et al., 2010a,b). Harvesting after a killing frost is a logical management decision for thermal–chemical conversion platforms and biopower because N, Ca, and other plant nutrients that function as contaminants in the thermochemical process are minimized in the plant tissue. Another alternative harvest time is to leave switchgrass standing in the field over winter and harvest the following spring (Adler et al., 2006). Delaying harvest until spring reduces yield by 20%–40% compared to harvesting in the fall after a killing frost. Yield losses associated with delaying harvest until spring may be acceptable if wildlife cover in winter is critical (Mitchell et al., 2012). With good harvest and fertility management, productive stands can be maintained indefinitely and certainly for more than 10 years (Mitchell et al., 2010a,b).

3.6.2 Nutrients Removal

Harvesting biomass, produced from the cultivation of perennial grasses such as switchgrass, removes large quantities of nutrients from the soil (Mitchell et al., 2008). Nitrogen is the most limiting nutrient for switchgrass production and is the most expensive annual production input. Nitrogen removal in switchgrass production systems is a function of biomass and N concentration, which increases as N fertilization rates increase (Vogel et al., 2002). Thus the reduction of nitrogen removal from the switchgrass production system has a positive effect on the economic and environmental sustainability of the system. It is quite important for the harvested material to have an N concentration as low as possible.

When harvesting is delayed to late winter the nitrogen content could decline from 1% to 0.6% and if the harvested biomass is 10 Mg ha^{-1} the removal will be 60 kg N ha^{-1} instead of 100 kg N ha^{-1}. Additionally, delaying harvest until spring reduces ash content and leached nutrients from the vegetation (Adler et al., 2006). In a multienvironmental study evaluating numerous N rates and harvest dates, biomass was optimized when switchgrass was harvested at the boot to postanthesis stage and fertilized with 120 kg N ha^{-1} (Vogel et al., 2002). At this harvest date and fertility level, the amount of N removed at harvest was similar to the amount of N applied, and soil NO_3–N did not increase throughout the study (Vogel et al., 2002). Consequently, it is important to consider the interaction of N rate and harvest and to replace in the production system only the needed N to prevent overfertilization and soil N accumulation.

3.6.3 Soil Carbon

As mentioned previously, switchgrass has an extensive perennial root system that protects soil from erosion and sequesters carbon (C) in the soil profile (Liebig et al., 2005). Soil organic carbon (SOC) typically increases rapidly when annual cropland is converted to switchgrass (Mitchell et al., 2012). Soil C levels on low-input switchgrass fields have been shown to increase over time, across soil depths, and are higher than adjacent cropland fields in the Northern Plains (Liebig et al., 2005). The amount of C sequestered depends on the climate, soil type, original soil C content, time, and replacement depth of C (Conant et al., 2001; Monti et al., 2011). It is reported (Liebig et al., 2008) that when switchgrass was cultivated for bioenergy on three marginally productive croplands in Nebraska an increase of 2.9 Mg C ha^{-1} yr^{-1} was recorded in the top soil in a period of 5 years. In another study in South Dakota where switchgrass was grown in former cropland, the SOC that was stored was 2.4–4.0 Mg ha^{-1} yr^{-1} at a 0–90 cm depth (Lee et al., 2007).

Switchgrass managed for bioenergy on multiple soil types in the Northern Plains was C negative, sequestering 4.42 Mg C ha^{-1} yr^{-1} into the soil profile (Frank et al., 2004). Nitrogen applications on switchgrass plots did not alter root C storage when compared with nonfertilized plots in a 2-year study (Ma et al., 2011). However, fertilization of grasslands increased the amount of C sequestered by 0.30 Mg ha^{-1} yr^{-1} in 42 studies throughout the world (Conant et al., 2001). Ma et al. (2011) reported that microbial biomass C was increased after switchgrass establishment and C mineralization was increased to 112% and 254% at depths of 0–0.15 m and 0.15–0.30 m, respectively. In several studies conducted in North America it has been found that the soil C was increased after switchgrass establishment and this increase varied from 1.7 to 10.1 Mg C ha^{-1} yr^{-1} (Lee et al., 2007; Frank et al., 2004; Ma et al., 2011; Zan et al., 2001).

3.6.4 Storage

Storage of switchgrass biomass should be considered in the cellulosic biorefineries since substantial biomass amounts should be safely stored on a year-round basis. Storage requirements and management are strongly dependent on how switchgrass will be harvested as well as on conversion technologies. The storage infrastructure requirements should be cost effective to maintain the desirable quality characteristics in relation to the conversion technology, and the harvesting schedules should be adjusted to regional weather factors (Imman et al., 2010).

In the near-term, switchgrass will be harvested and baled using commercial hay equipment. After harvest, the baling step bundles switchgrass into a more condensed form that will be easier to handle, transport, and store. The balers could be round or rectangular (square) ones. The round balers are larger (1.2–1.8 m in length) compared to rectangular bales (0.9–1.2 m in height and width and 1.8–2.4 m in length). For both methods of baling, the moisture content of switchgrass biomass at baling time should not exceed 18% so that composition degradation or spontaneous combustion can be avoided during storage. In the case of higher moisture content, field drying, prior to baling, is required to meet the safe moisture levels for baling. Balers can be modified to spray preservatives (e.g., propionic acid) onto hay limiting microbial growth and removing excess moisture for hay with 20%–25% moisture content (Collins and Owens, 2003).

There are advantages and disadvantages for both types of baling. The round baler has rather lower capital cost (one-fourth to one-third the capital cost) compared to the large rectangular baler (Turhollow et al., 1998) but its field capacity is lower because the baler needs to stop, wrap, and release the bale. On the contrary, there is no need for the rectangular balers to stop and thus the cost per unit of harvested area is less (Lazarus and Selley, 2005). Soon after baling, the rectangular bales should be removed from the field and protected from the rainfall because their flat surface does not shed water and thus the dry matter losses can be large (Collins and Owens, 2003).

The round bales have fewer storage losses compared to the large rectangular bales when stored outside, since they are less prone to water penetration, especially when they are net wrapped. It has been estimated that the net-wrapped round bales had 60%–70% lower dry matter losses compared to the round bales tied with plastic twine (Shinners and Boettcher, 2006). Rectangular bales tend to be easier to handle and load onto trucks for transport without road width restrictions. Double time is needed for the round bales to be loaded onto semitrailers compared to rectangular bales (Hess et al., 2009). Unless cellulosic biorefineries stipulate a certain baling method or alternative harvest method, both baling methods will likely occur for a given region.

Wet storage methods have been proposed for switchgrass in regions where drying conditions for baling operations are not possible because of high relative humidity and increased chance of precipitation even after harvest (Digman et al., 2010a). Switchgrass harvested using wet storage methods includes either a swather harvest, which is then chopped using a self-propelled forage harvester with a windrow pickup, or is directly cut with a self-propelled forage harvester with an attached rotary head that blows the material into adjacent semibulk trailers. The moisture content for switchgrass at time of pickup should be less than 10%. The main advantages of the wet storage methods are: reduced harvest costs, lower dry matter losses during storage, improved switchgrass cell wall recovery during enzymatic hydrolysis, and lower potential risk of fire during storage (Digman et al., 2010a). On the other hand, the main disadvantages of the wet storage method are the higher equipment and storage structure costs compared to a conventional baling system (Collins and Owens, 2003).

According to Hess et al. (2007), ideal storage management should preserve switchgrass biomass in an unaltered state during the storage period (Hess et al., 2007). Key factors in minimizing storage loss for bales are: (1) low moisture level, (2) low relative humidity and ambient temperatures, and (3) low biological activity so that dry losses and composition degradation can be avoided. Switchgrass with higher levels of N or with increased soluble sugars have increased potential for microbial growth and degradation during bale storage (Hess et al., 2009). Harvest dates determine overall N and soluble sugar content in switchgrass (Dien et al., 2006).

Some studies have been carried out to estimate dry matter losses during storage. Sanderson et al. (1997a,b) reported dry matter losses of 0%–2% when large round bales were stored inside for a period of 6–12 months and 5%–13% when the bales were stored outside. Switchgrass round bales rapped with twine when stored outside for a period of 6 months had 13% dry matter losses when they were left on sod and only 5% when they were left on crushed rock (Johnson et al., 1991). In southern Europe, both baling methods (round and rectangular bales) showed minimal storage loss and no visible microbial activity when stored under a sheltered roof (Monti et al., 2009).

3.7 Biomass Productivity

Several studies have been carried out worldwide to determine the biomass productivity of switchgrass and some of these studies are presented in Table 3.3. There is an obvious lack of studies that go further than 5 subsequent years. In the majority of the studies reported in Table 3.3 the yields were maximized in years 2–3 and in most of them the lowland varieties are being reported as more productive compared to upland varieties. It was found that lower yields should be anticipated when the crop is established on marginal and/or low fertility areas. According to Alexopoulou et al. (2017), mean yields of 12 Mg ha^{-1} (17-year period) could be achieved when switchgrass is established on marginal areas with shallow soil depth like the area of the trial.

A number of varieties (lowland and upland) are available from North America that have been found to be adapted to European conditions. The variety choice should be based on the latitude of the site on which switchgrass is to be established. Varieties originating from South American areas will do best in southern locations in Europe; however, they are still productive in northern Europe but over-winter survival may not be as good as varieties of northern origin. Results from the European switchgrass networks showed that switchgrass varieties can be grown further north in Europe than on the American continent. In the Switchgrass for Energy project it was found that Cave-in-Rock (upland) was adapted best to northwest European areas, while the lowland varieties Alamo and Kanlow performed best in southern Europe. Lowland varieties could be cultivated in northern Europe but winter survival problems could occur, especially at the establishment year.

In studies reported in the 1980s and 1990s (Myers and Dickerson, 1984; Christian and Elbersen, 1998) in the United States and northern Europe it was shown that a good stand of the crop could take several years and thereafter its lifespan could be more than 20 years. In later studies, Alexopoulou et al. (2017) reported that when the establishment is successful the yields could be maximized in the second year and no later than the third year. A reduction could be recorded in the two following years and thereafter the yields could be stabilized for at least a 10-year period. The delay in maximum production is most frequently experienced on cool wet clay soils in northern regions. In the Switchgrass for Energy project the trials that had been conducted in northern Europe (United Kingdom, the Netherlands, and Germany) reached peak yields at least 1 or 2 years later compared to the trials conducted in southern Europe (Italy and Greece).

In Fig. 3.11 long-term yields (17-year lifespan) are presented as a mean of 10 switchgrass varieties. The yields (Fig. 3.11) were maximized for the majority of the study varieties in year 2 and remained quite high in year 3. A decline was recorded in year 4 that was stronger in the fifth growing period, while from the sixth growing period and onward the yields were stabilized and were 10 Mg ha^{-1}. Overall, it can be pointed out that the lowland varieties were more productive than the upland varieties (11.15 vs. 10.64 Mg ha^{-1}). The superiority of lowland over upland varieties was quite stronger in the first 5 years of the trial.

Table 3.3 **Switchgrass productivity based on studies that have been carried out worldwide**

Site	Varieties (L: lowland, U: upland)	Trial duration	Yields ($Mg\,ha^{-1}$)	References
USA				
8 sites in Virginia, W. Virginia, Kentucky, N. Caroline, and Tennessee	L: Alamo and Kanlow U: Cave-in Rock (CIR) and Shelter	1992–2001 (10 years)	Yields varied were detected among the sites and the varieties under study. Mean yields of all factors: 15.8 for the lowland and 12.6 for the upland	Fike et al. (2006)
20 varieties and populations in Iowa	L: Alamo, Kanlow U: Blackwell, CIR, Pathfinder, Shelter, Forestburg, Trailblazer, Caddo, Carthage, Shawnee, Sunburst	1997–2001 (4 years)	The celling yields for all varieties and populations recorded in year 2. The most productive were the lowland varieties Kanlow (13.1) and Alamo (12.1). Mean yields averaged over all factors and years 9 $Mg\,ha^{-1}$	Lemus et al. (2002)
5 sites in Texas	L: Alamo, Kanlow, NCSU-1, NCSU-2, PMT-785 U: Caddo, Blackwell, Carthage, Summer	1992–96 (4 years)	The highest yields were recorded in year 3. Alamo was the best performing with yields varying from 8 to 20 $Mg\,ha^{-1}$ across the sites	Sanderson et al. (1999)
Alabama	L: Alamo, Kanlow U: Blackwell, CIR, Pathfinder, Summer, Trailblazer, and Native Kansas	1988–1990 (2 years)	Alamo and Kanlow were by far the best with yields of 17.5 and 13.8 $Mg\,ha^{-1}$ at the establishment year, while in the second year the yields were 34.6 and 23.2, respectively	Sladden et al. (1991)

Continued

Table 3.3 Switchgrass productivity based on studies that have been carried out worldwide—cont'd

Site	Varieties (L: lowland, U: upland)	Trial duration	Yields (Mg ha^{-1})	References
Europe				
Pisa, Italy	L: Alamo U: Blackwell	2000–04 (4 years)	At the establishment year the yields were too low (5 Mg ha^{-1}). Peak yields were recorded in year 2 (30 for Alamo and 15 for Blackwell). Yields reduction in year 3 and 4	Nasso et al. (2015)
Rothamsted, UK	L: Kanlow U: CIR, Pathfinder, Sunburst, Forestburg, Dacotah	1993–98 (5 years)	Mean yields of all years 7.3 Mg ha^{-1}, while the yields continued to increase until year 5 (9–14.6 Mg ha^{-1})	Christian et al. (2002)
2 sites in Thessaly, central Greece	L: Alamo	2010–12 (3 years)	In the fertile site the maximum yields were recorded in year 2, while in the less fertile site maximum yields were recorded in year 3 (27 vs. 14 Mg ha^{-1})	Giannoulis et al. (2016)
Bologna, Italy	L: Alamo, SL 93-3 U: Trailblazer, Shawnee	2002–06 (6 years)	Uplands were more productive than lowlands (14.7 vs. 11.9 Mg ha^{-1})	Monti et al. (2008)
Aliartos, Greece and Trisaia, Italy	10 varieties in Greece and 15 in Italy both lowland and upland; nine in common	1998–2002 (5 years)	In Greece the yields maximized in year 2, while in Italy the yields maximized in year 3. The mean yields of the 5 years in Greece were 14.4 and 7.9 Mg ha^{-1} in Italy. In both sites the lowland varieties were more productive than the upland varieties	Alexopoulou et al. 2008

Bologna, Italy and Aliartos, Greece	In Greece, five varieties were compared, while in Italy Alamo was the only variety	Greece: 1998–2015 Italy: 2002–12	At both sites the yields maximized in year 2. The mean yield (17 years) in Greece was 10 Mg ha^{-1} (0 kg N ha^{-1}), while the mean of 11 years in Italy was 13.6	Alexopoulou et al. (2015)
Aliartos, central Greece	L: Alamo, Forestburg, Kanlow U: CIR, Blackwell	1998–2015 (17 years)	The peak yields were recorded in year 2 (mean yield 20 Mg ha^{-1}). The mean yield of the 17 years was 12 Mg ha^{-1}. Lowlands were more productive than uplands	Alexopoulou et al. (2017)
Trisaia, Italy	15 varieties (lowland and upland)	1998–2001 (4 years)	The yields for all years maximized in year 3 (mean yield 12.4 Mg ha^{-1}). The best performing were SL93-2 and SL93-3 with 20.2 and 26.1, respectively.	Sharma et al. (2003)
China				
Yangling, Dingbian, and Guyuan	L: Alamo, Kanlow U: Blackwell, CIR, Forestburg, Nebraska 28, Pathfinder, Sunburst	Two established in 2006 and the third in 2009	In Yangling, Alamo was the best (44.2 Mg ha^{-1}), while in the other two sites (Guyuan and Dingbian) CIR was the best (10.59 and 9.36 Mg ha^{-1}, respectively).	Ma et al. (2011)
Beijing, China	L: Alamo, Kanlow, New York U: Ranlow, Rise, Ansai, Japan, Forestburg, Pathfinder, Blackwell, CIR, Trailblazer	2010–13	The three lowland varieties were the best performing among the 12 tested. The yields were quite low at the establishment year and maximized in year 3. CIR and Trailblazer were the best among the upland varieties	Yue et al. (2017)

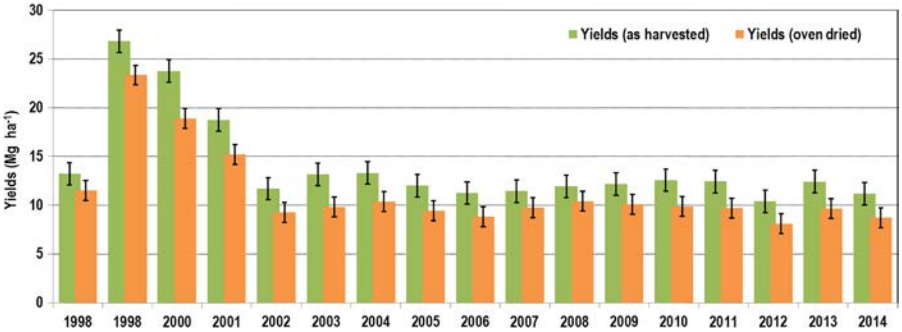

Figure 3.11 Yields ($\mathrm{Mg\,ha^{-1}}$, as harvested and oven dried) for a period of 17 subsequent years as a mean of 10 switchgrass varieties (six lowland and four upland).

3.8 Biomass Characterization and Uses

Initially, switchgrass had been selected in the 1940s as a forage crop for grazing or hay. Thus the research was scheduled in this direction, while switchgrass was also cultivated in selected areas for erosion control and as a vegetative filter to reduce runoff of soil and nutrients. In the 1980s switchgrass was proposed as an ideal energy crop for lignocellulosic feedstock production (combustion, conversion to liquid or gaseous forms). Nowadays, switchgrass is being investigated also as a source for fiber or pulp for paper, for phytoremediation, for biomaterials, for bioproducts, etc. The lignocellulosic feedstock that can be produced from perennial grasses such as switchgrass has been considered as low-cost biomass compared to oil, sugar, and starch-rich crops and fits well to the modern biobased economy concept to promote biorefineries. Switchgrass has been listed in the latest EU Directive 1513/2015 for the promotion of advanced biofuels, whose energy potential has been considered to be twice that of first-generation biofuels. Bioethanol produced from lignocellulosic feedstock shows enormous potential as an economically and environmentally sustainable renewable energy source.

Switchgrass, like all the other perennial grasses, is a lignocellulosic plant. Its chemical composition is primarily made up of structural polysaccharides (cellulose and hemicelluloses) and lignin (Scordia et al., 2014), and secondarily by small fractions of nonstructural components, such as extractives, proteins, lipids, pectin, and ash content (Wyman, 1994). According to Davison et al. (2013), the extractives are a complex mixture of components including sugars, terpenoids, and monolignols.

In the modern biorefineries there are two biorefinery platforms, a combination of different technologies to convert biomass to fuels and chemicals. In the biochemical platform, two pathways could be followed: (1) pretreatment, enzymatic hydrolysis, and fermentation and (2) anaerobic digestion, and the main products will be bioethanol and biogas, respectively. In the thermochemical platform, four pathways could be followed: torrefaction, pyrolysis, gasification, and combustion, and the main products will be solid torrefied biomass, bio-oil, syngas, and heat and energy. When switchgrass is used for nonenergy applications, three routes could be followed: chemical, physical, and biological to produce fine chemicals, fiber and building boards, sugars, proteins, and pectins.

In the biochemical process the biomass should be characterized in terms of structural and nonstructural polysaccharides, lignin, protein, and extractives, and the measurement unit of each compound is percentage (%) in 1 kg dry biomass (%w/w). In thermochemical processes, biomass should be characterized in terms of heating value (MJ kg^{-1}), proximate analysis (volatiles, ash content, and fixed carbon), and/or elementary analysis (% of C, H, O, N, and S). According to Xu et al. (2010), the chemical composition for biochemical conversion is cellulose (i.e., glucan 32%), hemicellulose (xylan 17.9%, arabinan 1.9%, and galactan 1.7%), and lignin (21.4%). The chemical composition of switchgrass for thermochemical conversion is gross calorific value 17.4 MJ kg^{-1}, C: 43.2%, H: 5.7%, O: 50.2%, and ash content 4.7 (McKendry, 2002).

In Table 3.4 the biomass characterization of 13 switchgrass varieties (lowland and upland varieties) for the thermochemical process is presented (Switchgrass for Energy project). Gross calorific value (MJ kg^{-1}) varies from 18.30 (Summer) to 18.92 (Carthage). The corresponding values for net calorific value vary from 17.0 to 17.62. The ash content varies among the tested varieties and the lowest ash content is measured for SL 94-1 (3.85%; lowland) and the highest for Summer (5.43%; upland). For all varieties the nitrogen content was quite low when the harvest took place quite late (mid-January) and ranged from 0.06% (Kanlow, SU 94-1) to 0.24% (Blackwell).

According to Clifton-Brown et al. (2015), perennial grasses are still at the early stages of development and improvement. Factors such as varieties (and/or genotypes), cultural practices (from establishment to final harvest), and the specific climatic conditions of the cultivation area could affect the biomass composition. It has been reported that when the nitrogen application was increasing the cell composition of switchgrass was affected (Allison et al., 2012) and the lignin content showed a 4.4% increase. A quite important parameter that affects the biomass composition is the time of the final harvest. When early harvests are applied the switchgrass biomass is characterized by higher ash and mineral content that negatively affects the thermochemical conversion processes. On the other hand, it has been shown (Jensen et al., 2016) that when the final harvest is postponed (late winter harvests) the quality criteria for thermochemical conversion are improved. It has been reported that the stand age could affect the biomass composition with the reduction of hemicellulose or the replacement of hemicellulose in the cell matrix by lignin (Allison et al., 2012).

Feedstock quality, however, depends upon the bioenergy conversion system used to convert the biomass to fuel (e.g., thermochemical, biochemical, or direct combustion system; Adler et al., 2006). High mineral concentration, notably nitrogen and ash concentrations, decrease the efficiency of direct combustion and thermochemical conversion systems (Ablevor et al., 1992). Lignin, on the other hand, is important for thermochemical conversion processes, but since it also binds with cellulose and hemicellulose, higher concentrations of lignin also limit the availability of cellulose and hemicellulose during biochemical conversion processes, resulting in reduced biofuel yields (Adler et al., 2006; Trebbi, 1993). In addition to the abovementioned structural carbohydrates (i.e., cellulose and hemicellulose), switchgrass also contains

Table 3.4 Biomass composition for thermochemical conversion

Varieties	Gross calorific value	Net calorific value	Volatiles	Ash	Fixed C	C	H	N
Lowland								
Alamo	18.49	17.25	78.41	5.06	16.53	46.08	5.88	0.15
Kanlow	18.71	17.42	79.31	4.16	16.53	45.85	6.12	0.06
Pangburn	18.43	17.21	78.58	4.70	16.72	45.64	5.79	0.18
SL 93-2	18.59	17.30	79.02	4.14	16.84	45.85	6.08	0.18
SL 93-3	18.65	17.33	79.03	4.39	16.57	45.09	6.24	0.20
SL 94-1	18.70	17.40	79.57	3.85	16.58	45.97	6.17	0.08
Upland								
Caddo	18.70	17.44	79.08	4.97	15.96	45.14	5.96	0.14
Carthage	18.92	17.62	79.29	4.28	16.41	45.78	6.16	0.07
CIR	18.67	17.38	79.67	4.30	16.02	45.44	6.10	0.09
Forestburg	18.63	17.31	79.31	4.16	16.53	45.50	6.27	0.10
Blackwell	18.46	17.23	79.40	4.70	15.90	45.69	5.81	0.24
SU 94-1	18.59	17.29	79.12	4.03	16.85	45.05	6.15	0.06
Summer	18.30	17.00	78.64	5.43	15.93	44.74	6.13	0.14

From CRES; unpublished data.

nonstructural carbohydrates including sucrose, glucose, fructose, and starch. These sugars are not present in very high concentrations compared to the structural carbohydrates, but can be used as a source of fermentable sugars for liquid fuel production (Dien et al., 2006; Johnson et al., 2007). Concentrations of these important feedstock components can vary significantly due to geographic location, genetic factors, plant maturity, and agronomic practices (Adler et al., 2006; Vogel et al., 2002). While many switchgrass compositional and harvest management studies address variability in forage quality, understanding of ecotype variation in switchgrass quality for bioenergy applications is more limited.

Native prairie grasses are commonly used in phytoremediation strategies. Their extensive fibrous root system can penetrate up to 10 ft below the surface and can result in a greater surface area than other vegetation (Aprill and Sims, 1990). Phytoremediation studies have shown that switchgrass, alone or in combination with other native prairie grasses, is capable of removing atrazine from the environment. Stands of switchgrass in combination with other native prairie grasses can reduce atrazine in leachate by 43% as well as promote degradation in the rhizosphere (Belden and Coats, 2004).

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Giant Reed: From Production to End Use

4

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4.1 Introduction

Giant reed (*Arundo donax* L.) is a potentially high-yielding nonfood crop that could meet EU market requirements for energy and advanced biofuels, paper and pulp, and construction of building materials. In contrast to miscanthus and switchgrass, giant reed has the advantage of being a native of southern Europe. However, it has never been investigated because of the absence of any market. On the contrary, in certain environments it was considered as an invasive species and as such it was subjected to eradication programs. The new market for biomass and especially for advanced biofuels for transport (road, air, marine) as well as for other industrial products warrants more focus on the crop and its potentialities.

Successful cultivation of biomass crops for energy, advanced biofuels, pulp purposes, etc. greatly depends on biomass raw material cost. Reducing biomass cost could be achieved by increasing biomass yields through genetic improvement and application of effective cultivation techniques. In addition, the 2030 Climate and Energy package calls for significant greenhouse gas (GHG) reductions in transport: 20% in 2030 relative to the emissions of 2008 and 60% in 2050 relative to the emissions from transport in 1990. Taking into account that biomass production involves the highest part of GHG, energy crop cultivation including giant reed that is already listed as a potential feedstock has to be carried out in a sustainable way, such as growing on idle or marginal lands to avoid the need to bring significant amounts of new land into agricultural production, while not conflicting with food crops over good agricultural lands and irrigation water.

Giant reed (*A. donax* L.) has several attractive characteristics that could make it the champion of biomass crops:

- Certain wild-grown unimproved populations give dry matter biomass yields up to 40 Mg DM ha^{-1} or even higher (80–90 Mg DM ha^{-1}) at optimum cultivation practices.
- Giant reed has a good starting point in terms of yields, being one of the most productive perennial species among the presently cultivated biomass crops in Europe.

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- It is a lodging-resistant plant.
- It is tolerant to high temperatures and limited water supplies.
- It is one of the most cost-effective energy crops, with low annual inputs (water, nitrogen pesticides/insecticides).
- Its robust root system and ground cover as well as its living stems during winter offer valuable protection against soil erosion in the sloping lands and erosion-vulnerable soils, good soil quality (increased fertility, organic matter, and nutrient retention), and biodiversity (cover for native wildlife).
- It can be used as a carbon sink filter system for removing agrochemicals from water and for phytoremediation.
- It presents great prospects by selection and genetic improvement as well as by defining the most appropriate cultivation techniques to allow higher yields.

Over the years many researchers have focused considerable effort on revealing the origin of the plant, its physiology, as well as its cultivation and harvesting methods. On the other hand, a number of studies have been focused on the ability of the plant to be used in a number of applications, e.g., energy and biofuels, paper and pulp, building materials, etc. The aim of this chapter is to compile the results from these studies and provide a concise overview of *A. donax* as a very attractive and promising candidate species for many uses.

As such the chapter consists of five sections:

4.1.1 Giant Reed Origin and Taxonomy

This section gives a brief overview of the studies focused on giant reed origin and taxonomy, casting light on the genetic profile of the plant and the ways it was distributed around the globe.

4.1.2 Plant Physiology

This section discusses the uncommon phytosynthetic capacity of the plant and its resource use efficiency, namely, radiation, nutrient, and water use efficiency under several growing conditions. Saline tolerance of the plant is particularly detailed and suggestions regarding new ecotypes of improved tolerance toward biophysical constraints are presented.

4.1.3 Agronomy

This section evaluates the agronomy of the plant and provides detailed information on its propagation and establishment, nutrient and irrigation requirements, weed management, and crop protection. Plant eradication is also addressed.

4.1.4 Harvesting and Logistics

This section ascertains how the plant can be mechanically harvested to allow a commercial scale-up of its cultivation. Harvest times, methods, and equipment are discussed along with storage and logistics, as well as potential biomass pretreatment before its final use.

4.1.5 Biomass Productivity and Uses

This section reviews assessments of the potential uses of the plant and compiles results for its biomass characterization and exploration for biogas/biomethane production, paper/pulp production, energy and advanced biofuels, and other uses.

4.2 Giant Reed Origin and Taxonomy

Giant reed (*A. donax* L.) is a C_3 perennial rhizomatous grass belonging to the Gramineae family (Poaceae) (Rossa et al., 1998; Lewandowski et al., 2003), to which other perennial grasses also belong, for example, switchgrass (*Panicum virgatum*), *Miscanthus* ssp., and reed canary grass (*Phalaris arundinacea*) (Lewandowski et al., 2003). Giant reed classification is presented in Table 4.1.

At least five species of *A. donax* have been identified across subtropical Eurasia in a number of phylogenetic studies (Hardion et al., 2012, 2014a,b), four of which were established in the Mediterranean area (*A. donax* L., *Arundo micrantha* Lam., *Arundo plinii*, and *Arundo donaciformis* (Loisel)).

Although the origin of *A. donax* L. is still uncertain, Bucci et al. (2013) suggest that, depending on the number of chromosomes reported in the study (110), it could be the result of: (1) the crossing between *A. plinni* and a diploid of the same species, resulting in a sterile triploid, or (2) the crossing between a fertile tetraploid of *A. plinii* and *Phragmites australis*, resulting in a sterile hybrid (Fig. 4.1).

Moreover, difficulties in the chromosome counting in *A. donax* L. have been observed due to the small size and high number of chromosomes of this species. Different studies have reported a number of chromosomes that vary from 40 (Mariani et al., 2010) to 108 (Christopher and Abraham, 1971) and 110 (Pizzolongo, 1962; Bucci et al., 2013).

Table 4.1 ***Arundo donax* L. classification according to the Integrated Taxonomic Information System (ITIS, 2017)**

Kingdom	**Plantae**
Subkingdom	Viridiplantae
Infrakingdom	Streptophyta
Superdivision	Embryophyta
Division	Tracheophyta
Subdivision	Spermatophyta
Class	Magnoliopsida
Superorder	Lilianae
Order	Poales
Family	Poaceae
Genus	*Arundo*
Species	*Arundo donax* L.

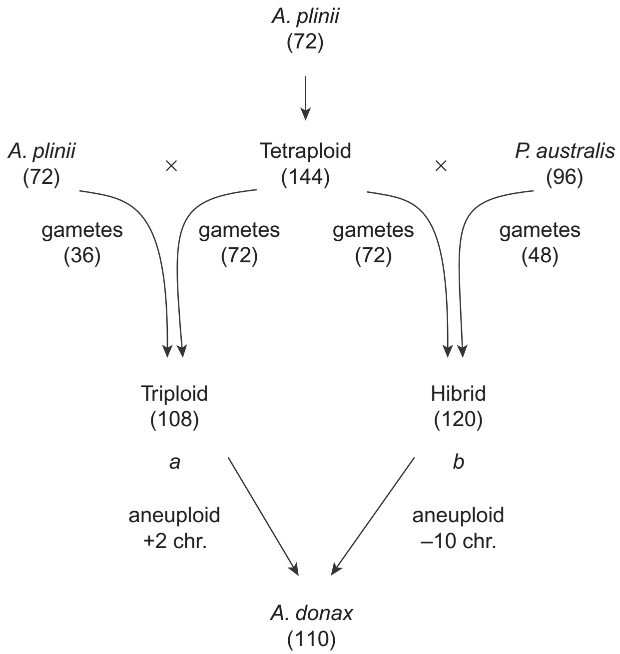

Figure 4.1 Hypothesis regarding the phylogenetic origin of *Arundo donax* L. (Bucci et al., 2013).

Existence of varieties of this species is reported (Perdue, 1958), the most known being *A. donax* var. *variegata* (var. *versicolor*, var. *picta*) ($2n=40$), which is a diminutive of the typical *A. donax*, grows denser, and produces a higher number of culms.

Although there is no agreement on the localization of the area in which *A. donax* L. was originated, an East Asia origin has been reported by many authors (Polunin and Huxley, 1987; Fornell, 1990). According to Mariani et al. (2010), an amplified fragment length polymorphism analysis of *A. donax* L. samples recollected from 80 different sites supported a monophyletic origin and suggested that it originated in Asia and later spread to different subtropical wetlands and warm-temperature regions of Europe, Africa, North America, and Oceania. Nowadays, many giant reed studies have been reported in different habitats in several countries such as Italy (Angelini et al., 2009; Cosentino et al., 2006, 2014; Mantineo et al., 2009; Mariani et al., 2010; Borin et al., 2013; Haworth et al., 2016), Spain (Sánchez et al., 2015, 2016a, 2017), Greece (Christou et al., 2003), the United States (Di Tomaso and Healey, 2003; Herrera and Dudley, 2003; Khudamrongsawat et al., 2004; Ahmad et al., 2008; Balogh et al., 2012; Minogue and Wright, 2016; Wunderlin et al., 2017), South Africa (Rossa et al., 1998), Egypt (Galal and Shehata, 2016), and Australia (Williams et al., 2008) among other countries.

Although *A. donax* L. produces flowers, no viable seeds have been reported in several studies (Boose and Holt, 1999; Dudley, 2000; Spencer et al., 2005; Williams et al., 2009; Mariani et al., 2010; Balogh et al., 2012). However, the reason for this nonviability of *A. donax* L. seeds is not fully defined. According to Bhanwra et al. (1982)

and Balogh et al. (2012), sterility results from failures in the division of the mother cell of the megaspores, whereas Mariani et al. (2010) and Hardion et al. (2012) reported that *A. donax* L. meiosis would occur normally in both male and female gametogenesis, but afterward, the haploid gametophytic generation would be deeply anomalous. Despite studies suggesting that polyploidy events do not seem to influence the reproductive problems in *A. donax* L. (Hardion et al., 2015), the failures of their gametogenesis remain poorly understood.

Consequently, its propagation and diffusion are carried out mainly by rhizome extension, rhizome fragmentation, or flood dispersal (Boose and Holt, 1999; Lewandowski et al., 2003; Boland, 2006; Mariani et al., 2010; Ceotto and Di Candilo, 2010; Saltonstall et al., 2010; Pilu et al., 2013). Because of this vegetative reproduction, low or moderate genetic variability between *A. donax* L. plants has been observed (Lewandowski et al., 2003; Khudamrongsawat et al., 2004; Ahmad et al., 2008; Touchell et al., 2016).

Its rapid growth rate and easy propagation (Herrera and Dudley, 2003) along with its tolerance to unfavorable environments and infertile soils have made *A. donax* L. widespread in a wide range of areas and naturalized in areas where it was not a native species (Barney and Di Tomaso, 2008; Barney et al., 2009). The fact that *A. donax* L. has been considered as an invasive species by some authors (Dudley, 2000; Herrera and Dudley, 2003; Ahmad et al., 2008; Mack, 2008; Barney and Di Tomaso, 2008; Barney et al., 2009; Balogh et al., 2012; Pilu et al., 2012) has opened the debate about the use of an invasive plant as an energy crop. However, its unviable seeds and its use in marginal land with no flooding are not barriers to the use of *A. donax* L. as an energy crop for biomass production.

4.3 Plant Physiology

4.3.1 Uncommon Photosynthetic Capacity

Giant reed (*A. donax* L.) is a high-yielding, lignocellulosic, perennial grass suitable to warm and semiarid environments (Cosentino et al., 2006, 2008; Mantineo et al., 2009; Zegada-Lizarazu et al., 2010; Cosentino et al., 2014). The highest productivity of giant reed is achieved in warm growing conditions despite the fact that it uses a C_3 photosynthetic pathway. In sites with high spring/summer temperatures and solar radiation, giant reed is as competitive as C_4 plants, or even more so in semiarid conditions dominated by limited water availability (Lewandowski et al., 2003; Cosentino et al., 2007, 2014). However, it is not completely clear how giant reed is so competitive in such conditions, where only a C_4 species might be expected to be so photosynthetically efficient.

Mean values of leaf photosynthetic rates of CO_2 uptake for many C_3 plants are around 18–20 μmol CO_2 $m^{-2}\,s^{-1}$, while that for C_4 plants usually exceed 20 μmol CO_2 m^{-2} (Mohr and Schopfer, 1995).

In a natural giant reed stand, located in an estuarine in South Africa, leaf photosynthesis was between 19.8 and 36.7 μmol $m^{-2}\,s^{-1}$ (Rossa et al., 1998). Similar results were reported by Haworth et al. (2016), who conducted a physiological study in a semiarid Mediterranean environment by using two contrasting giant reed ecotypes (in terms of biomass yield), under well-watered and drought stress treatments. Both ecotypes exhibited high levels of net photosynthesis (~33–38 μmol CO_2 m^{-2} s^{-1}) prior to the cessation of irrigation, with no statistical difference between ecotypes. CO_2 assimilation rates were maintained under well-watered conditions, with the exception of the latter measurement where air temperatures were lower than the first two measurement times. As soil drying progressed in the drought stress treatment, the two ecotypes showed identical CO_2 uptake decline (around 67% reduction).

In nonlimiting conditions of soil water availability and nitrogen fertilization in a field trial under semiarid Mediterranean conditions, giant reed CO_2 assimilation rates were close to 24 μmol m^{-2} s^{-1} throughout 3 experimental years. However, soil water availability, nitrogen fertilization, and time of measurement significantly influenced CO_2 uptake (Cosentino et al., 2016).

Papazoglou et al. (2005) found a net photosynthesis of 15.3–25.4 μmol m^{-2} s^{-1} for the first year and 18.7–34.0 μmol m^{-2} s^{-1} for the second year in giant reed grown in pots irrigated with increasing concentrations of heavy metal solutions of Cd and Ni, with no significant differences between treatments and dates of measurement. In a field experiment conducted in North Central Florida on a deep-drained fine sand soil, Erickson et al. (2012) measured approximately 30 μmol CO_2 m^{-2} s^{-1} for giant reed. In pot experiments under water and salinity stresses, Sánchez et al. (2015) reported levels of 2–35 μmol CO_2 m^{-2} s^{-1} across different giant reed clones; however, significant differences were detected between the control and stress treatments, the level of stress within the treatment, the time of measurement, and even among clones (Table 4.2).

It is quite clear that giant reed has an uncommon high photosynthetic capacity as compared to other C_3 species, and very similar to those of C_4 species. This high photosynthetic capacity has been related to the absence of both CO_2 uptake saturation and electron transport rate through photosystem II at a photosynthetic photon flux density as high as 2500 μmol m^{-2} s^{-1}, suggesting neither photoinhibition nor photosystem II damage (Rossa et al., 1998).

Webster et al. (2016) raised a number of questions to gain insights into the high productivity of giant reed. The authors conducted a study to determine photosynthetic and photorespiratory parameters in a natural stand of giant reed grown in southern Portugal. The experiment confirmed that the photosynthetic capacity of giant reed in full sunlight is high compared to other C_3 species, and comparable to C_4 bioenergy grasses. This was related to the high capacity for both ribulose-1:5-bisphosphate (RuBP)-limited and RuBP-saturated photosynthesis (which were near double the average for C_3 species) rather than either lower photorespiratory rates or high stomatal conductance. Furthermore, CO_2 uptake during periods of low light intensity, as in the lower, shaded canopy around dawn and dusk or in cloudy days, may be aided by relatively high maximum quantum yields of CO_2 assimilation and high leaf absorbance.

However, as a C_3 crop, giant reed shows a high rate of leaf transpiration. In the field, under unlimited soil water availability, the transpiration rate reached 7.5 mmol H_2O m^{-2} s^{-1} (Cosentino et al., 2016), much higher than many C_4 grasses (Erickson et al., 2012; Mann et al., 2013; Nackley et al., 2014). Thus giant reed is able to achieve its high photosynthetic rates, but with substantial transpiration; however, it is still more efficient than most C_3 species (Webster et al., 2016).

Table 4.2 **Leaf photosynthetic rates of CO_2 uptake in giant reed grown under different experimental conditions and sites**

Experimental	Site latitude and longitude	Leaf photosynthesis (µmol CO_2 $m^{-2}s^{-1}$)	References
Natural conditions	Field conditions (29°53′S, 31°00′E)	19.8–36.7	Rossa et al. (1998)
Two-contrasting ecotypes in rainfed and well-watered conditions	Field conditions (37°25′N, 15°03′E)	11.0–38.0	Haworth et al. (2016)
Contaminated (Cd and Ni) soil	Controlled environment	15.3–34	Papazoglou et al. (2005)
N fertilization and soil water availability	Field conditions (37°25′N, 15°03′E)	1.6–23.6	Cosentino et al. (2016)
Comparison of C_3 and C_4 perennial grasses	Field conditions (29°24′N, 82°8′W)	30.0	Erickson et al. (2012)
Clone response to increasing salt and water stress	Controlled environment	2.0–35.0	Sánchez et al. (2015)
Natural conditions (ambient and low O_2 concentration)	Field conditions (38°38′N, 9°11′W)	30.2–34.8	Webster et al. (2016)

4.3.2 Resource Use Efficiency

Biomass productivity can be determined by the net increase in plant dry matter per unit of light intercepted [radiation use efficiency (RUE)], per unit of water transpired [water use efficiency (WUE)], or per nutrient taken up [nutrient use efficiency (NUE)] (Kiniry et al., 2011).

An overview of the resource use efficiency of giant reed under different growing conditions is shown in Table 4.3.

4.3.2.1 Radiation Use Efficiency

Giant reed grows in warm environments at increasing conditions of temperatures and solar radiation. It has a fast canopy closure and growth rate, which enables this crop to intercept almost all available photosynthetically active radiation (PAR) when the leaf area index (LAI) is greater than 4.0, which is reached in the first 2–3 months after spring regrowth in semiarid Mediterranean areas (Cosentino et al., 2014).

Only a few reports studied the RUE of giant reed. In a field trial, where radiation, temperature, and water availability were not limiting factors during the summer period in northern Italy, Nassi o Di Nasso et al. (2011a) compared mature stands of giant reed and *Miscanthus* × *giganteus*. The calculated RUE values were 2.02 g MJ^{-1} for giant reed and 2.70 MJ^{-1} for miscanthus, which are in line with RUE values of C_3 and C_4 species, respectively.

Table 4.3 Resource use efficiency

Experiment	**Site latitude and longitude**	**RUE g MJ^{-1}**	**NUE g g^{-1}**	**PUE g g^{-1}**	**KUE g g^{-1}**	**WUE^{a}**	**References**
Comparison of *Arundo donax* and *Miscanthus* × *giganteus*	Field conditions (4340′N, 1019′E)	2.02	–	–	–	–	Nassi o di Nasso et al. (2011a)
Comparison of *A. donax* and *Sorghum bicolor*	Field conditions (44°32′N, 11°11′E)	5.74	–	–	–	–	Ceotto et al. (2013)
Comparison of *A. donax* and *M.* × *giganteus*	Field conditions (43°40′N, 10°19′E)	–	316–467	884–1183	108–136	–	Nassi o di Nasso et al. (2011b)
N fertilization levels in a long-term stand	Field conditions (44°33′N, 11°02′E)	–	168.4–251.6	–	–	–	Monti and Zegada-Lizarazu (2016)
Harvest time and frequency	Field conditions (43°40′N, 10°20′E)	–	168–314	766–1112	62–114	–	Dragoni et al. (2016)
N fertilization and soil water availability	Field conditions (37°25′N, 1503′E)	1.26–1.94	4.3–103.5	–	–	1.8–5.0	Cosentino et al. (2016)
Comparison of C_3 and C_4 perennial grasses	Field conditions (29°24′N, 82°8′W)	–	–	–	–	1.19–2.47	Erickson et al. (2012)
Comparison of *M.* × *giganteus* and giant reed under extreme drought to inundated soil	Controlled environment	–	–	–	–	0.75–4.03	Mann et al. (2013)
Increasing CO_2 of 400 and 800 μmol mol^{-1}	Controlled environment	–	–	–	–	4.0–12.0	Nackley et al. (2014)
N fertilization and soil water availability	Field conditions (37°23′N, 14°21′E)	–	–	–	–	0.93–7.63	Mantineo et al. (2009)
N fertilization and soil water availability	Field conditions (37°25′N, 15°03′E)	–	–	–	–	1.71–4.51	Cosentino et al. (2014)
Comparison of *M.* × *giganteus* and giant reed in lysimeter systems	Controlled environment	–	–	–	–	2.9–3.5	Triana et al. (2014)

KUE, Potassium use efficiency; *NUE*, nitrogen use efficiency; *PUE*, phosphorus use efficiency; *RUE*, radiation use efficiency; *WUE*, water use efficiency in giant reed grown under different experimental conditions.

[a] WUE was calculated either as μmol of CO_2 uptake per mol of H_2O transpired (instantaneous WUE) or as the ratio of the aboveground dry matter yield at harvest to the cumulative evapotranspiration or to the water used by the crop (g L^{-1}).

Later on, Ceotto et al. (2013) compared giant reed to the annual C_4 crop sweet sorghum in the alluvial plain of the Po Valley, northern Italy. The RUE in this case was much higher in giant reed than sweet sorghum, accounting for $5.74\,\mathrm{g\,MJ^{-1}}$ intercepted PAR for giant reed and $3.48\,\mathrm{g\,MJ^{-1}}$ for sweet sorghum. While the RUE of *Sorghum* parallels values found in the literature, such remarkable RUE for a C_3 crop (giant reed) might be considered too high and resemble the theoretical limit for a C_4 canopy (Loomis and Amthor, 1999). Indeed, the authors attributed the extremely high RUE as a consequence of small sampling areas for biomass yield estimate that might have caused an RUE overestimation. However, other hypotheses for such high RUE were related to an optimal canopy structure coupled with high LAI and a very low light extinction coefficient (k), similar to that attributed to crops with erect leaves. In this regard, Cooper (1970) showed that the growth rate of six forage grasses was strongly influenced by k; the lower the k, the higher the growth rate.

Cosentino et al. (2016) conducted a field trial in southern Italy comparing giant reed under different levels of nitrogen fertilization and soil water availability. It was found that giant reed increases its RUE proportionally as nitrogen and available water were increased. RUE values ranged between $1.26\,\mathrm{g\,MJ^{-1}}$ in rainfed and unfertilized conditions, to $1.94\,\mathrm{g\,MJ^{-1}}$ when $120\,\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$ and well-watered treatments were applied. Such RUE values were lower as compared with that of *M.* × *giganteus* grown in well-watered, $2.33\,\mathrm{g\,MJ^{-1}}$, conditions but higher than those in rainfed conditions in the same experimental area ($1.24\,\mathrm{g\,MJ^{-1}}$) (Cosentino et al., 2007). The k of giant reed, although low (0.38–0.44), was slightly higher than that by Ceotto et al. (2013), but lower than the k of *M.* × *giganteus* (0.56) grown in the same experimental area (Cosentino et al., 2007).

4.3.2.2 Nutrient Use Efficiency

The NUE of a giant reed grown in northern Italy in a changing harvest time was $316\,\mathrm{g\,g^{-1}}$ in October and $467\,\mathrm{g\,g^{-1}}$ in late January. Phosphorus use efficiency (PUE) was 884 and $1183\,\mathrm{g\,g^{-1}}$ in October and late January, respectively, while potassium use efficiency (KUE) was 108 and $136\,\mathrm{g\,g^{-1}}$ in the same order of harvest times (Nassi o di Nasso et al., 2011b).

In a changing harvest frequency (single or double harvest in one growing season) of giant reed in a north Mediterranean environment, it was found that for all three macronutrients (N, P, and K) there was a general increase in the use efficiencies from double harvest to single harvest (Dragoni et al., 2016). NUE in double harvest was significantly less efficient than single harvest (168 vs. $314\,\mathrm{g\,g^{-1}}$, respectively). Also PUE varied largely between double and single frequency (average across treatments of 766 and $1112\,\mathrm{g\,g^{-1}}$, respectively). KUE was considerably lower than those of other macronutrients, as a consequence of the greater amounts removed by the crop. Again, remarkable KUE differences were observed between double and single harvest (average across treatments of 62 and $114\,\mathrm{g\,g^{-1}}$, respectively).

Monti and Zegada-Lizarazu (2016) reported a significant effect of year and nitrogen fertilization on NUE of a long-term plantation of giant reed in the north Mediterranean. As the stand became older the NUE decreased, and by increasing the nitrogen amount, the NUE decreased as well. Averaged across the experimental period, NUE increased from 179.7 g g^{-1} when 160 kg N ha^{-1} yr^{-1} was applied, to 218.5 g g^{-1} in unfertilized conditions. At the fifth-year-old stand, NUE was 251.6 g g^{-1}, averaged across fertilization treatment, to 168.4 g g^{-1} when the stand was at its 16th year.

Agronomic NUE in different treatments of nitrogen fertilization and soil water availability in a semiarid Mediterranean environment greatly changed according to the experimental treatments and stand age (Cosentino et al., 2016). The effect of N fertilization on NUE was significant only at the first and second growing season, but was not at the third, more mature stand. This is explained by the ability of perennial grasses to regulate and mobilize nutrients upward (from belowground to aboveground) during the growth seasons and downward (from aboveground to belowground) after the onset of senescence. In that experiment, NUE varied between 4.3 and 103.5 kg kg N^{-1}.

4.3.2.3 Water Use Efficiency

As mentioned earlier, the photosynthetic capacity of giant reed is high, but with substantial transpiration, leading to low, or at least lower, WUE than many C_4 crops (Erickson et al., 2012; Mann et al., 2013; Nackley et al., 2014; Triana et al., 2014).

In a side-by-side comparison of C_3 and C_4 perennial grasses in field conditions in North Central Florida, Erickson et al. (2012) showed WUE values in giant reed of 1.19 and 2.47 g kg^{-1} in subsequent growth years, lower than those of the C_4 energy cane and elephant grass.

Mann et al. (2013) calculated the instantaneous WUE as μmol of CO_2 uptake per mol of H_2O transpired in flooded, mild drought, severe drought, and control conditions in pots established with giant reed. The highest values were found at mild drought conditions (4.03) followed by the control (3.54) and by the flooded conditions (3.36). Severe water stress led to a WUE of only 0.75 μmol CO_2 mol H_2O^{-1}.

Nackley et al. (2014) significantly doubled the instantaneous WUE of giant reed raising the CO_2 concentration from 400 to 800 μmol mol^{-1} in growth chambers, and the cuvette CO_2 concentration of the portable photosynthesis equipment from 400 to 800 μmol mol^{-1} (from 4.0–5.0 to 6.0–12.0 μmol CO_2 mol H_2O^{-1}). In lysimeter systems, Triana et al. (2014) calculated the WUE as the ratio of the aboveground dry yield at harvest to the cumulative evapotranspiration in giant reed and miscanthus. The authors showed that in general, miscanthus had a higher WUE than giant reed. However, statistical differences between the species were recorded only in the first growth year, 4.3 g L^{-1} in miscanthus and 2.9 g L^{-1} in giant reed, while similar values were recorded in the subsequent year (about 3.5 g L^{-1}).

In a 5-year field trial in a semiarid Mediterranean environment, Mantineo et al. (2009) showed WUEs (as the ratio of the aboveground dry yield at harvest to the water used by the crop) of 0.93–1.0 g L^{-1} at establishment, when irrigation water was provided at 25% or 75% of the maximum evapotranspiration restoration. Such WUE increased to 5.04–7.63 g L^{-1} at the fourth and fifth years of growth, when the irrigation was ceased and crops were grown in rainfed conditions.

In a similar environment, Cosentino et al. (2014) found a linear negative relationship between WUE and the water used by the crop. Significantly higher WUE values were observed in rainfed (3.74–4.03 g L^{-1}) than in intermediate (2.60–3.67 g L^{-1}) and well-watered conditions (2.08–3.45 g L^{-1}). Nitrogen fertilization led to greater values of WUE; the slope of the linear regression indicated that WUE decreased by 0.18 g at each 100 mm of crop water use in the unfertilized treatment, and by 0.19 and 0.23 g when 60 and 120 kg N ha^{-1} were supplied, respectively.

Finally, Webster et al. (2016), calculated the intrinsic leaf water use efficiency (LWUE) in giant reed (as the ratio of CO_2 assimilation over stomatal conductance), measuring values of 62.9–66.0 μmol mol^{-1}. The LWUE was generally higher than other herbaceous species (43 μmol mol^{-1}), but much lower than for C_4 species such as miscanthus and switchgrass (115 and 107 μmol mol^{-1}).

Overall, reviewed studies hereto agree that giant reed has relatively high transpiration rates and will therefore use more water than many C_3 as well as C_4 biomass crops (Erickson et al., 2012; Mann et al., 2013; Triana et al., 2014; Nackley et al., 2014; Webster et al., 2016). However, proper water management improves WUE in giant reed. In this regard, Cosentino et al. (2016) showed close relationships between the stomatal conductance and WUE, and the available soil water content and WUE in a field trial in a semiarid Mediterranean environment. WUE was maximized when the available soil water content was between 40% and 60% of the field capacity. Under these conditions of soil moisture, transpiration rate decreased due to partial stomata closure and net photosynthesis remained unchanged at its highest levels resulting in improved WUE. Furthermore, predawn leaf water potential being at the highest levels indicated no occurrence of plant water stress.

4.3.3 Salinity Tolerance

Water stress and salinity are among the most important environmental limitations affecting plant growth, development, and yield in arid, semiarid, and Mediterranean environments (Araus et al., 2003; Munns and Tester, 2008; FAO, 2012). Giant reed, being a warm-season C_3 grass, is grown under increasing conditions of air temperatures and global solar radiation, which, however, correspond to seasonal rainfall reduction and rise in potential evapotranspiration.

With regard to salinity, a preliminary study aimed at comparing 40 giant reed clones collected in contrasting environments in southern Italy (Cosentino et al., 2006). Plantlets were transplanted in pots and irrigated with Na solutions of 4 and 8 dS m^{-1}. Significant differences were found between salinity levels, as well as between clones (Cosentino et al., 2013). The regular irrigation with saline water caused an increase of the soil electrical conductivity that reached 2.2 dS m^{-1} in the control, 6.3 dS m^{-1} in the mild, and 9.1 dS m^{-1} in the severe salinity level. Across the average of 40 clones, it was shown that salt stress led to a reduced stomata conductance, and thus net photosynthesis reduced as well. This translated into the reduction of main plant growth parameters (e.g., biomass yield, main stem height, specific leaf area, LAI, and leaf water content). However, specific leaf weight and leaf-to-stem ratio showed an opposite trend. On the other hand, mild salinity level led to the highest belowground (root and rhizomes) dry weights. Across the average of 40 clones, biomass yield was reduced by 44% at severe salinity levels as compared with the control, while reduction was only 15.3% at mild salinity. However, some clones performed better than others.

Afterward, Sánchez et al. (2015) studied the stress effect on the contrasting clones resulting from Cosentino et al. (2013). In this experiment, salinity levels were raised (up to 16 dS m^{-1}) and water stress was added as a new treatment. Furthermore, a control giant reed clone (from the Piccoplant company) and another giant reed clone from Spain (Martinensis) were added. A stress susceptibility index was used to discriminate between clones under water and salinity stress. It was found that the "Agrigento" clone (from the south of Italy) was suitable for growing in Mediterranean areas under water stress conditions, due its smaller decrease in net photosynthesis, relative water content, and green leaf area. In contrast, Martinensis followed by Cefalú and Fondachello (both from the south of Italy) were reported as suitable for cultivation in marginal lands where salinity predominates. Finally, Martinensis and Piccoplant were suggested as the most suitable clones for growing under both water and salinity stress conditions for biomass production.

Nackley and Kim (2015) in a pot experiment observed no plant mortality at very high levels of salinity (42 dS m^{-1}). A strong negative correlation between increasing salinity and biomass accumulation was found. According to their findings, the authors considered giant reed "moderately sensitive," because it was able to maintain >50% of its relative growth when salinity was <12 dS m^{-1}.

As drought-prone and saline-prone lands are increasing worldwide due to the rise in evapotranspiration and use of poor-quality irrigation water, the assessment of resilient species to avoid competition or displacement of food production, providing raw material for renewable energy markets, should be strongly promoted. In this regard, Sánchez et al. (2016b) conducted an interesting geographic information system analysis with the aim of assessing the surplus saline lands in Spain (areas classified simultaneously as saline and saline-prone lands) to grow giant reed. The authors modeled agronomically attainable yield means of 17.4 t dry matter ha^{-1} in a soil electrical conductivity range of 6–9 dS m^{-1}. When soil salinity (7.9 dS m^{-1}) was combined with water stress (64% water deficit), 26.4% and 29.5% yield reductions were reported.

Overall, the reviewed literature showed that giant reed is a drought-resistant and moderately high saline-tolerant species. Although low genetic variability and seed sterility constrain the development of more productive and/or drought-/salt-tolerant genotypes, it would be worthwhile investigating wild germplasm for identification of those traits that confer tolerance to many biophysical constraints and where to grow bioenergy crops. For instance, the role of abscisic acid (ABA), the hormone that is known to control stomatal closure, and isoprene emission, a proxy of ABA formation under certain circumstances, in the drought response of giant reed has been investigated in two contrasting ecotypes (Haworth et al., 2016). Levels of free ABA and fixed glycosylated ABA were different between ecotypes, and increased earlier in response to the onset of water deficit in "ecotype 6"; however, as drought progressed, the leaves of "ecotype 20" showed greater concentrations of both forms of ABA that correlated with a decline in stomatal conductance but no alteration in net photosynthesis. Rates of isoprene emission during the initial period of soil drying showed a 34.6% increase in ecotype 6 and a 15.1% increase in ecotype 20, although significant differences were not observed between water treatment and ecotypes. The reduction in stomatal conductance induced by increased ABA in water stress conditions may be indicative of biochemical protection to maintain foliar water content before soil water availability declines to critical levels.

4.4 Agronomy

4.4.1 Propagation and Establishment

The establishment period is the most critical aspect of giant reed cultivation and influences the long-term productivity and economy of plant life. It was demonstrated that transplanting rhizomes between the end of February and the middle of March is an effective propagation method in Mediterranean zones of Europe (Copani et al., 2009). Due to seed sterility, giant reed commonly propagates by rhizome and shoot fragmentation during flooding events, and by shoot layering (Boose and Holt, 1999; Mariani et al., 2010; Pilu et al., 2013; Boland, 2006; Ceotto and Di Candilo, 2010; Saltonstall et al., 2010); only a few reports indicate that giant reed could be reproduced by seeds (Perdue, 1958; Bor, 1970; Brach and Song, 2006). Giant reed is usually established by rhizomes, micropropagated plants produced in garden centers as whole stems, or stem cuttings; rhizomes or micropropagated plantlets generally ensure higher guarantees of a successful establishment, particularly large rhizome pieces with well-developed buds (Fig. 4.2). However, the main drawback of propagation via rhizomes is the higher costs compared to stem cuttings and whole-stem planting (Copani et al., 2009, 2010). The lack of an effective mechanization systems for planting rhizomes is one of the reasons for the high costs. In the case of stem propagation, the main problem is the low sprouting capacity of the buds, so they form less dense stands, resulting in irregular plant population density and lower biomass yields than expected.

4.4.2 Nutrient Requirements and Fertilization

The response to N fertilization of giant reed is highly variable across different environments, growth conditions, and crop age. In some cases, giant reed was found to

Figure 4.2 Propagation and establishment methods of giant reed: by rhizomes (left), by whole stems/stem cuttings (center), and by micropropagated plants produced in garden centers (right).

significantly respond to N fertilization only during the first 4 years after establishment (Angelini et al., 2005). The authors attributed this decreasing fertilization effect to a more mature and extensive root system and developed rhizomes (Angelini et al., 2005). N fertilization seems to become more important for belowground biomass development with plant age; a continuous increase in giant reed rhizome biomass from the second to the third growing season was reported, accounting for 30% and 40% of the total biomass produced (Nassi o Di Nasso et al., 2011a, 2013). Similarly, in a semiarid environment, Cosentino et al. (2014) suggested that fertilization was more important at the establishment than in subsequent years; however, it should be recognized that N fertilization in the establishment year might also considerably increase weed competition. On the other hand, long-term studies indicated that depending on soil nutrient status and root development status, the response to N fertilization was either significant or unchanged. In a long-term study (9 years), for example, carried out in a low-input marginal cropping system affected by climatic constraints, soil erosion, and low soil organic matter (Fagnano et al., 2015), a 16% increment (in average 2.3 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$) on biomass productivity due to a fertilization level of 100 $\mathrm{kg\,N\,ha^{-1}}$ was indicated. Such increments were obtained with a total N uptake of 57–69 $\mathrm{kg\,N\,ha^{-1}}$. In another long-term study (16 years) carried out also in a marginal area with similar soil texture, but under different environmental conditions (Monti and Zegada-Lizarazu, 2016), an increment between 12% and 17% in biomass productivity was reported with a fertilization level between 80 and 160 $\mathrm{kg\,N\,ha^{-1}}$ and an uptake rate of 90 and 117 $\mathrm{kg\,N\,ha^{-1}}$, respectively. The similar but minimal biomass increments in the aforementioned studies, carried out in either case under marginal soil conditions, suggest that giant reed at maturity may reach a sort of threshold increment potential beyond which yield increases are of limited cost effectiveness, regardless the N fertilization level.

In general, various reasons could be given for the low N requirements of giant reed such as internal pool of nutrients recycling capacity in close relation to their rhizome structure, high nutrient use efficiency, potential associations with N-fixing bacteria, extensive root system and great soil canopy cover that limit nutrient losses through leaching, soil type, previous cropping, and interactions between N fertilization and temperature and water availability (Palmer et al., 2014). In most cases, however, soil N availability seems to play a preponderant role. It is possible that the relative prone positive response, though small in absolute numbers, of giant reed stands to fertilization could be simply related to the fact that with time the continual removal of N in the harvested dry biomass may gradually but inexorably deplete the soil and rhizome reserves and therefore there is increasing supply and demand of N as the plant ages.

Therefore it is plausible that the response of giant reed to N fertilization will be minimal or even zero, as long as the soil nitrogen availability, the rhizome reserves, and other N inputs such as N deposition and/or biological nitrogen fixation are sufficient to supply the estimated typical uptake rates. It is very important to take into consideration not only the crops' requirements, but also the environmental context where these crops are grown to prevent soil N depletion, while determining and synchronizing their fertilization needs. Aligning the environment N stocks with the crop uptake capacity in a soil–plant–atmosphere model (Strullu et al., 2011) could be useful for a more precise determination of the long-term fertilization needs of giant reed grown under different environmental conditions and cultural practices. In general, in medium fertility soils it could be recommended to apply between 150 and 200 kg ha^{-1} of P and K. N fertilization, on the other hand, is an extremely tricky issue because not only does it meet giant reed requirements, it also increases weed competition. So, the decision whether to distribute N fertilizer in the first year will depend on each case, taking into account weed presence and the inherent soil fertility level. In the following growing season, the nutrient requirements are not that high, and about 50–80 kg N ha^{-1} could be enough to maintain satisfactory yields in the long term.

4.4.3 Irrigation Requirements

Giant reed is a species that is considered invasive in the riparian habitats of the US coastal areas or in areas near rivers and lakes (Fig. 4.3). Opinions are divided about the plant's risks. The US Department of Agriculture declared it is considered to be a *transformer* species because it dramatically alters habitats and ecological processes. In the United States and particularly in California Arundo is considered a "*highly aggressive, non-native plant species that has invaded riparian areas and floodplains, displacing native plants and degrading habitats, posing also a significant fire risk*" (California Invasive Plant Council). On the other hand, the European Commission called the giant reed one of the most cost-effective and environmentally friendly crops (http://www.newsobserver.com), which is also endorsed by the recently announced (Brussels, February 23, 2017) Renewable Energy Directive (RED II), still in its draft version.

Giant reed is an invasive, resilient species able to grow under less favorable conditions than many other plants. The habitat distribution that giant reed is found in ranges from very wet clay to relatively dry sandy soils. It has been classified as halophyte and as a facultative wetland (Lewandowski et al., 2003; Williams et al., 2009; Mann et al., 2013). A number of findings have suggested giant reed as a facultative wetland species that can grow on equal terms at soil field capacity and flooded soils, achieving an impressive productivity, while reducing its potential biomass yield at mild and severe water stresses (Mann et al., 2013; Cosentino et al., 2014). Its drought resistance is attributed to the rhizomes and deeply penetrating roots that reach deep-seated water tables.

In accordance with recent debates concerning food and bioenergy crops, it has been suggested to grow the latter on less productive, marginal lands to avoid land competition. Thus there has been a steady interest in testing giant reed under water or salinity stress conditions.

In a 3-year field trial in a semiarid Mediterranean environment, the effect of the available soil water content on morphological traits and biomass yield of giant reed was studied (Cosentino et al., 2014). Generally, stem density was not affected by the irrigation treatment; on the other hand, stem height, from the elongation phase up to harvest, was significantly higher in well-watered than in mild-watered conditions, which, in turn, was higher than rainfed treatment along the experimental period. The LAI was higher in well-watered conditions only at the phase of maximum

Figure 4.3 Wide distribution of giant reed habitats.

development, but was not at harvest time. The biomass dry matter yield was affected by the irrigation water: yields were 29.8%, 34.6%, and 40.0% higher in well-watered than rainfed conditions. The gap reduced to 13.7%, 12.2%, and 21.9% between well-watered and mild-watered conditions at the first, second, and third post-establishment growing seasons, respectively. Thus mild-watered treatment (50% of the maximum evapotranspiration restoration) not only conveyed to relevant biomass yield (a reduction of 21.9% as compared with the well-watered treatment) but allowed a saving of about 50% of irrigation water, a rising problem in agricultural activity due to the cost and availability of water in Mediterranean-type climates. In the same study, an asymptotic nonlinear relationship was developed to predict biomass yields of giant reed as a function of crop water use in a semiarid Mediterranean environment. The model explained well the relation between two variables, and how the yield tended to increase almost linearly up to 450 mm of water, whereas the increase was less than proportional at greater water amounts. Giant reed is a high water-demanding crop; however, its root system might allow the crop to uptake water at soil layers as deep as 150 cm in rainfed conditions or up to 180 cm when irrigation water is constantly applied (Cosentino et al., 2014).

Giant reed was cultivated under high water and nitrogen inputs in Mediterranean environments by Borin et al. (2013) and achieved the highest productivity reported as early as the year after transplanting (85 and 98 Mg ha^{-1} of dry matter in Padova and Bologna, respectively). Yields continue to be high from the second to the third year (62 and 51 Mg ha^{-1} of dry matter in the two regions) (Table 4.4). In that experiment the total amount of water received through irrigation and rainfall, an average of the second and third growing seasons, was 973 and 1235 mm in Padova and Bologna, respectively. The contribution of rainfall to total water availability was 44%–45% in Padova.

Irrigation effect on giant reed growth and yields was compared in Central Greece (Vagia) and south Italy (Catania), two Mediterranean countries prone to water-shortage conditions, especially in late spring and summer months (Christou et al., 2001, 2003). The irrigation treatments were similar: I_0 = dry control, I_1 = 50% of maximum evapotranspiration, and I_2 = 100% of maximum evapotranspiration. Averaged over the first three growing seasons, the aforementioned treatments corresponded to 306.9 and 281.8 mm for I_0 in Greece and Italy, respectively, while the respective quantities were 727.9 and 555.1 for I_1 and 1088.9 and 835.4 mm for I_2. Highest yields were achieved by the highest irrigation rate (averaged over the nitrogen treatments): 30 Mg ha^{-1} of dry matter in Vagia and 40 Mg ha^{-1} in Catania in the third year (Fig. 4.4). In the dry control the highest yields were also achieved in the third year with 10 Mg ha^{-1} of dry matter in Greece and 20 Mg ha^{-1} in Catania (averaged over the nitrogen fertilization treatments). Yields of the fourth growing season showed a decline in both experiments. Irrigation rates and age of plantation had significant effect on yields, both on stem and on total yields, while nitrogen effect was only occasional (Fig. 4.5).

Irrigation rates and age of plantation affected growth and yields (stem and total yields). However, significant effects were detected only between the dry control and the full irrigation, which means that high yields can be obtained with half maximum evapotranspiration restoration—accompanied by a high dose of nitrogen fertilizer in the case of Catania. In the best growing conditions (full irrigation and high nitrogen rates)

Table 4.4 ***Arundo donax*** **productivity**

Locations	**Yields (t ha^{-1} dm)**						**References and general remarks**
	Y1	**Y2**	**Y3**	**Y4**	**Y5/6**	**Mean**	
Italy							
Pisa	10–22	28–48	21–35		19–25	37.7	Angelini et al. (2005, 2009) Yield range due to fertilization and harvest time Mean: averaged from Y1 to Y12
Bologna					26.1	16.2–19.5	Monti and Zegada-Lizarazu (2016) Mean values are averaged from second to 16th growing periods and range according to nitrogen fertilization treatments
Central Italy	~13–22			~15–26			Nassi o Di Nasso et al. (2010) Yield range due to fertilization and harvest time
Sicily	6.1	31.1	38.8	34.9	27		Mantineo et al. (2009) Yield averaged over irrigation and nitrogen fertilization treatments
Bologna Calabria Catania Padua	4.0–23.0	29–99	~51–99				Borin et al. (2013) Yield range due to trial sites and harvest times. The low yields in Calabria and Catania and the high yields in Padua and Bologna
Catania	–	10.0–18.3	13.4–28.8	12.9–28.9			Cosentino et al. (2006, 2014) Yield range due to irrigation treatments and populations

Greece							
Aliartos		19.9	25.1	18.8			Christou et al. (2001) and Lewandowski et al. (2003) Yields averaged over irrigation and nitrogen fertilization treatments
	1.4	5.7	12.4	14.3	16.1		Christou et al. (2015) Yields averaged over irrigation and nitrogen fertilization treatments in a marginal land
United States							
Arkansas	~2.5–6	~30–40	~50			41.5	Burner et al. (2015) Yield range due to irrigation treatments Mean: averaged from Y1 to Y3
North Carolina	2.9	23.8	20.8	24.8		22.8–27.4	Palmer et al. (2014) Mean yields are averaged over nitrogen fertilization treatments in the third and fourth years of growth. Mean yield range is due to mountainous and coastal sites
Oklahoma	4.7	21.4	25.3				Kering et al. (2012) Annual yields averaged over four nitrogen treatments
Georgia	5.3–7.0	8.5–10.1	4.1–7.1	2.9–5.8		4.8–7.3	Knoll et al. (2012) Yield range due to different clones
Australia							
	45.2						Williams et al. (2009) The plant was irrigated with winery wastewater

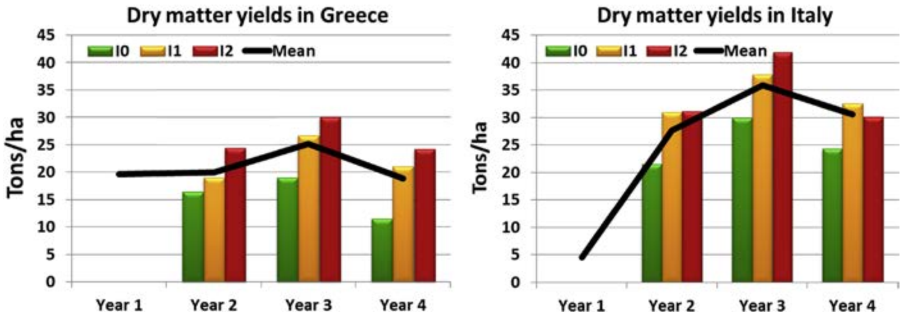

Figure 4.4 Dry matter yields of *Arundo donax* for three irrigation rates (averaged over fertilization) and three subsequent years in Greece (Vagia) and Italy (Catania) (Christou et al., 2003).

Figure 4.5 Non-irrigated *Arundo donax* plants (left) and well-irrigated plants (right).

the WUE was almost similar in both localities and ranged between 2 and 3 g d mL^{-1}. With a reduction of the water consumed by the crop the WUE tended to increase attaining maximum values of 6 g d mL^{-1} in Vagia and 10 g d mL^{-1} in Catania. This means that in conditions of low soil water availability, the plant was able to improve its WUE and maintain a high level of production, reaching, to a certain extent, the maximum productivity obtained by the fully watered plants. This means that *A. donax* could be successfully grown under moderate irrigation without losing its high productivity level.

4.4.4 Weed Management and Crop Protection

Giant reed is characterized by high rusticity and limited susceptibility to pathogens and insects, therefore it does not usually require chemical treatments. The leaf and stems of giant reed contain, among other chemical components, alkaloids and silica (Jackson and Nunez, 1964; Perdue, 1958) that enhance plant protection against parasites and predators. Moreover, due to its large leaf mass and high growth rates, giant reed does not face significant weed competition from the second year onward since it substantially reduces light and water availability for its understory.

For safe establishment, however, herbicide application is recommended in the first year (Zegada-Lizarazu et al., 2013). Apart from specific herbicides, mechanical weeding, especially if coupled with the incorporation of fertilizers, can be an effective practice to control weeds.

4.4.5 Giant Reed Eradication

Persistence of giant reed arises from its vigorous rhizomatous root system, especially in old well-established stands. Several eradication/control measures are proposed (i.e., cultural, biological, mechanical, and chemical). Among these, the most effective one is plowing followed by broad-spectrum systemic herbicides and crop desiccants (Bell, 1997; Spencer et al., 2008). A single foliar application of 3%–5% late in the growing season is considered the best approach in terms of efficacy, labor costs, and reduced environmental effects (Spencer et al., 2008). Late-season application ensures the efficient movement of herbicides from the canopy to the root system. In some cases, however, herbicide applications may be needed more than once to properly/completely eradicate the crop. On the other hand, mechanical removal, although effective, is costly and impractical in large-scale plantations (Lawson et al., 2005) since the use of hammer-flail mowers, root plows, rakes, etc. for such purpose would lead to major soil disturbances.

4.5 Harvesting and Logistics of *Arundo donax* L.

4.5.1 Harvesting Times

The conventional harvest operation of Arundo relies on a single harvest per year, generally performed during the winter season, when aboveground organs are senescent. The collection of the biomass in this period has a good fuel quality due to lower moisture content and reduced concentration of detrimental elements such as minerals and nutrients, which before winter are mobilized to the rhizomes. Giant reed culms that remain standing in the field during winter reach a moisture content of about 50%, while during the pick of the vegetation stage in early summer this parameter is close to 70% (Smith and Slater, 2011). In addition, the plantation during winter is not producing new sprouts; this avoids damage to new vegetation that would be provoked by the passage of harvest machines.

However, with recent interest in using giant reed for biogas production, the summer harvest or the double harvest (in summer and fall) have been reconsidered as suitable harvest management periods, providing higher yields in biogas compared to traditional winter harvest (Ragaglini et al., 2014). This is mainly due to the quality of the biomass obtained, whose characteristics are more suitable for anaerobic digestion (Dragoni et al., 2015). However, these findings should be further validated through studies focused on the regrowth capability of giant reed and overall productivity over time, since repeated cutting may result in depletion of belowground reserves and weakening of regrowth, thus leading to a reduced lifespan of the plantation.

The several biomass conversion technologies have different prerequisites and constraints for feedstock quality. For instance, crop maturity has a negative effect on specific biogas yields, while juvenile traits (e.g., high proportion of leaves, high moisture content) tend to be detrimental for thermochemical processes and beneficial for anaerobic digestion (Ragaglini et al., 2014). Therefore even if winter harvest remains the most widely used practice, further studies should be performed to evaluate the long-term impact of the different harvest management strategies on the crop final uses. This will define the most appropriate harvesting methods matching each biomass conversion process, thus supporting management of the crops toward different supply chains.

4.5.2 Harvesting Methods and Equipment

The harvest of *A. donax* is fully mechanized and can be performed using different strategies. The choice of one harvest method over another is determined by several aspects, such as crop status, biomass moisture content at harvest time, final use, required biomass quality parameters, logistics, availability of equipment, and type of storage. The experience gained by mechanization during the years has led to define four possible harvest strategies for Arundo as schematized in Fig. 4.6.

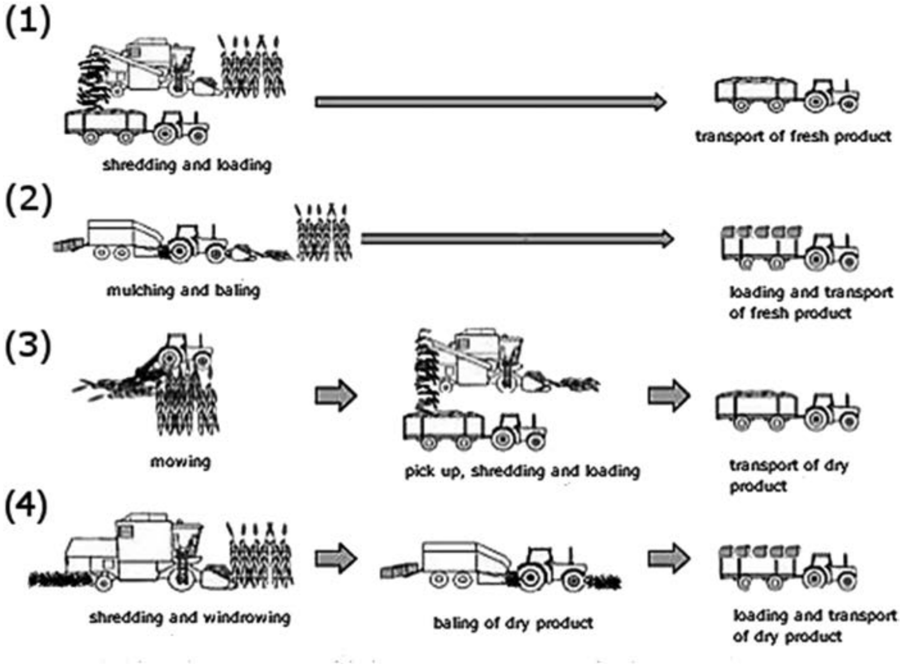

Figure 4.6 Scheme of the four possible harvest yards for Arundo.
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4.5.2.1 System 1: Shredding and Loading of the Fresh Product

This type of system involves the use of a self-propelled forage harvester (SPFH) commonly employed for the harvesting of silage maize. The forager is flanked by a tractor-trailer unit receiving the chopped biomass, which is then delivered to a collection point. Harvest tests have been performed using the SPFH Claas Jaguar 850 equipped with an OrbisRU 450XTRA row-independent maize head (Fig. 4.7).

The head has a working width of 4.5 m. The transmissions are composed of gears that move three horizontal self-sharpening cutting discs. After cutting, the biomass is pushed into the feeding channel of the machine through two vertical toothed rollers. The shredding system of the machine is composed of a horizontal rotary drum 750 mm long and with a diameter of 630 mm. The drum presents two lines of knives in a "V"-shaped configuration. The speed of rotation of the drum is synchronized with that of the feeding rollers; this allows the cutting length of the biomass to be varied in a limited way according to the machine settings. During performance tests (Acampora et al., 2014), the chipped product is discharged in a three-axle trailer with a steering turntable (SilverCar SCR314) towed by a Fendt 312 Vario tractor.

The machine in standard field conditions demonstrated an effective field capacity of 1.34 ha h^{-1}, but particle size analysis made on the fresh product revealed a high presence of fine fractions below a centimeter. This factor impedes the immediate use of the biomass as fuel for combustion as feeding systems of power plants can become clogged, and there is also the risk of harmful fermentations during storage.

The small particle size of the biomass produced by SPFHs is the main limit in the application of this harvest method. New mechanical solutions should be identified to increase the size of the product and improve the air permeability. The higher product size is expected to allow faster drying under any given conditions, decrease the likelihood of fermentative phenomena, and improve fuel quality. The comminution was

Figure 4.7 Front view of the Claas Jaguar 850 equipped the OrbisRU 450XTRA. © CREA-IT.

studied intensely in woody species, evaluating the effects of several parameters on particle size distribution such as the type of chipper, blade wear, screen type, or tree part (Spinelli et al., 2013; Nati et al., 2010). However, these aspects for herbaceous species have not yet been studied in much detail, although the physical characteristics of the product are likewise important.

In this regard, investigations were performed by CREA-IT in collaboration with the machine constructor Spapperi Ltd. within the research project OPTIMA funded by the European Union. The project activities included the design of a prototype for giant reed harvesting, capable of improving the particle size of the product to increase its storability. The prototype built has a working width of 2.8 m and is composed of two main parts: (1) a cutting system coupled to two vertical rotors conveying the plants toward the in-feed rollers and (2) a disc chipper rotating on a horizontal axis equipped with two knives in a radial position (Fig. 4.8).

The two components are connected by two counterrotating toothed rollers having the function of picking up the plants to convey at the disc chipper. The chipping system is based on the typology of forestry chippers. The positions of the main disc holders and the blade holder have been modified to enlarge the cutting opening and favor the lengthening of the cut. The functional scheme foresees the use of a tractor with reversible drive and a tractor-trailer combination moving parallel to the machine where the chips are blown by a swiveling gooseneck. When loaded, the tractor-trailed unit moves to a collection point where the feedstock is discharged. Comparative tests have been performed to evaluate the quality of the product obtained by SPFH and the

Figure 4.8 Spapperi Ltd. prototype of Arundo harvesting system.
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prototype. These tests revealed that the material produced with the prototype had a particle size significantly higher than the SPFH, with a mean particle length of 41.3 versus 8.8 mm (Pari et al., 2015a,b).

4.5.2.2 System 2: Mulching and Baling of the Fresh Product

The second yard utilized for the harvest of giant reed consists of the application of a mulcher and a baler, contemporarily operating on the same tractor equipped with rear-frontal power take-off and machine attachment systems. This system allows cutting, shredding, and baling the biomass in a single pass, with the front part of the tractor equipped with the shredding/windrower machine, and the rear part equipped with the baler (Fig. 4.9).

Harvest tests were performed in 2015 (Martelli et al., 2015) using the RM 280 BIO biotriturator produced by Nobili S.r.l. and two types of balers produced by KUHN, respectively the model VB2160 round baler and the model LSB1290 large square baler. The biotriturator is formed by a flattening frame and a movable front hood with roller—both hydraulically adjustable—favoring the introduction of the still standing canes inside the shredding chamber. The shredding system consists of a horizontal rotor equipped with 64 “Y”--shaped knives. Thanks to an auger mounted below the rotor, whose transfer rate is hydraulically adjustable, the mulcher provides both windrowing and shredding; this allows subsequent collection of biomass through balers. The overall weight of the machine is 1500 kg.

The round baler VB2160 is formed by a pickup system 2.1 m large, on which are mounted four lines of metal teeth designed to provide uniform entrance and versatility in different soil profile conditions. The biomass is then cut by a knife system and pushed into the press chamber through a feeding system formed by iron teeth and one large screw. The press chamber works through the combination of three rollers and five flexible belts.

The bales produced during the trials had a diameter of 1.6 m and a length of 1.2 m, with an average weight of 378 kg (fresh basis) considering a moisture content at harvest

Figure 4.9 Harvest yard formed by a mulcher (Nobili S.r.l.) and baler (Khun S.A.). © http://www.nobili.com.

time of 35%. The large square baler LSB1290, also known as high-density press, presents a pickup system similar to the round baler but with a working width of 2.3 m. The cut system in this case is formed by a horizontal rotor equipped with 23 knives. The length of the product to be baled can be modified by varying the number of knives mounted onto the rotor, as they are removable. The feeding system is formed by a singular feeding fork that pushes the biomass into a prepress chamber. The press chamber is 3 m long in total, with a press system based on four hydraulic cylinders. Variation of the bale pressure can be applied from the tractor cabin through a specific command.

The square bales produced during the test with Arundo were 0.9 m high, 1.2 m wide, and 2.1 m long, with an average weight of 583 kg (fresh basis) considering a moisture content at harvest time of 35%. As this large square baler absorbs much more power than the other, a more powerful one was used in the test. Indeed, it has been verified that a tractor having 150 kW power was enough for harvest, while the square baler required a 200 kW power tractor. The effective field capacity of both harvest yards have been evaluated by scientists on the basis of the working times and varied from 0.62 ha h^{-1} of the yard with round baler to 0.74 ha h^{-1} achieved with the square baler. The difference was mainly because unloading of the round bales requires the tractor to stop, while unloading of the square bales can be done with the tractor in motion.

4.5.2.3 System 3: Mowing, Pickup, Shredding, and Loading of the Dry Product

This harvest yard requires two passes, one with a tractor equipped with a mowing system and another with an SPFH equipped with a pickup system. The advantage of this system in comparison with the others is that the product collected is already dry and ready for conversion. The disadvantage is undoubtedly the repeated passages of the machines in the field, which may increase the harvest cost and can provoke damage to the soil structure as a consequence of compaction.

Harvest tests have been performed in Italy (Acampora et al., 2014) using a lateral mower Galfrè FR/G 190, characterized by a working width of 1.9 m and a cutting system formed by rotary drums, each one equipped with eight knives (Fig. 4.10). The machine has an articulated system placed between the two rotors that allows working in different soil profile conditions, avoiding the crush of the turfgrass also on high-slope working conditions. All transmission organs and gears are closed inside a box in an oil bath. The mowed plants are left to dry in the field and are successively collected with an SPFH equipped with a pickup head. The model Claas PU 300 HD was tested in Italy in 2013. This head is characterized by a horizontal toothed roller and a posterior screw that works as a convey system toward the feeding channel. Two front wheels regulate the working height of pickup according to soil conditions. The shredded dry material is unloaded onto a trailer attached to a tractor that works in parallel with the machine (Fig. 4.11).

4.5.2.4 System 4: Shredding, Windrowing, and Baling of the Dry Product

As in the previous system, this harvest yard requires two passes and obtains a dry product ready for immediate conversion. In this case, the product is immediately

Figure 4.10 Lateral mower Galfrè FR/G 190.
© CREA-IT

Figure 4.11 Claas PU 300 HD during collection of dry Arundo biomass.
© CREA-IT.

mowed, shredded, and windrowed in the field for drying using SPFH equipped with a Kemper-type head. Successively, the dry biomass can be collected using round balers or high-density square balers and then collected from the field and transported to the power plant.

Harvest tests using this system were performed in Spain (Curt et al., 2011). The SPFH was a John Deere 6910 mounting a Kemper Champion 450 harvesting header. To allow biomass crushing, the knives of the drum cutter head were removed, and plants were crushed and left windrowed on the ground. The measured working height and working width were, respectively, 0.20–0.25 and 1.9 m. Successively the biomass was collected by means of the square baler Claas Quadrant 2100 (Fig. 4.12), powered by a Fendt 916 Vario tractor (144 kW). It must be pointed out that for the test, the original Claas baler pickup was removed and replaced with a T-2400 mulcher (Serrat).

4.5.3 Storage and Logistics

Apart from sites and climatic conditions, biomass production of giant reed is concentrated in determined periods of the year. This short-time availability is not aligned with energy demand, which varies among countries according to geographical location

Figure 4.12 Modified Class Quadrant 2100 baler used to collect Arundo.
© UPS.

and season. This imbalance implies the need for biomass storage over longer periods to guarantee constant biomass supplies also during the period of highest demand. Another reason for requiring biomass storage is the initial moisture content of the fuel delivered to the power plant. Usually, the moisture content of fresh giant reed biomass is about 50% if harvested during senescence. However, to obtain an efficient conversion (referred to as combustion and syngas production) the level of moisture content should be below 30% (Kofman, 2006). A short-term period of storage at the storage site is normally envisaged as biomass power plants can process only certain amounts of fuel per day and direct delivery is almost impossible. Indeed, power plants always have a buffer zone for the storage of fuel so that they can be less affected by fluctuations and delays in the delivery chain (Thörnqvist and Jirjir, 1990).

Until now, a few trials on storage of giant reed biomass have been carried out. Infield drying seems to be the most economic and rapid method to obtain proper material for combustion. To evaluate the changes in fuel quality and dry matter losses that occur over time, scientists stored chopped giant reed stems in field windrows for 20 days, achieving moisture content lower than 15% (Curt et al., 2011). Successively, the dry material was stored outdoors in bales for 8 months without noticing relevant changes in physical, chemical, and energetic properties of the biomass. In another study performed in Italy, giant reed was stored in stem bundles to test several storage times from December to March and monitor the trend of moisture content over time. In this case, the initial moisture content of the plant was always around 50%, while acceptable levels of moisture for energy conversion through combustion were reached in all cases in late spring (Sanzone and Sortino, 2010).

Small-scale experiments (Pari et al., 2015a,b) using chopped giant reed were performed during summer in central Italy using three different methods: material stored 1 month outdoors in ventilated bins, material stored 1 month outdoors in perforated bins, material stored 1 month outdoors in piles on plastic platforms. Drying rate and dry matter losses were significantly different according to the method used as shown

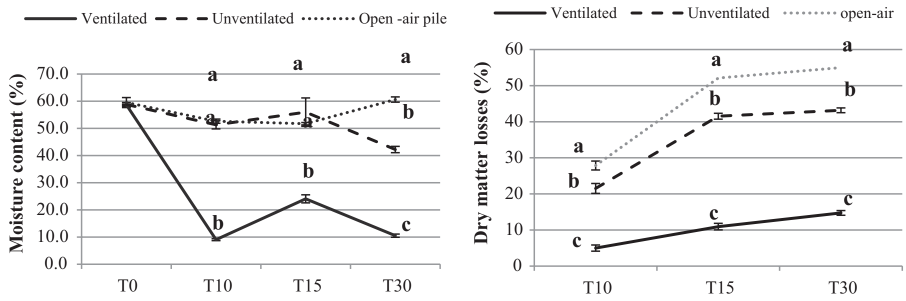

Figure 4.13 Trend of moisture content in Arundo biomass under different storage conditions (Pari et al., 2015).

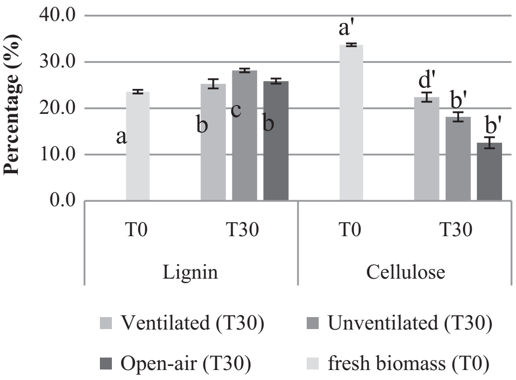

Figure 4.14 Variation in lignin and cellulose in Arundo due to different storage conditions (Pari et al., 2015).

in Fig. 4.13. The moisture content of the fresh biomass was about 59%. After 10 days of storage, the average moisture content of the feedstock put in the ventilated bins decreased by about 50%, while in unventilated bins and open-air piles it decreased by about 7%. Dry matter losses were consistently higher in open-air piles and unventilated treatments than those in ventilated ones. At the end of storage the losses were 40% higher in open-air piles and 28% in unventilated bins.

The effect of different storage systems was evaluated also on the principal polymeric component of the biomass. Variation in lignin and cellulose content was monitored during the storage time. Fig. 4.14 reports the percentage composition in lignin and cellulose at the beginning and end of storage. No relevant variations were observed in lignin content among different storage treatments, while cellulose content decreased more or less according to the storage method used. In particular, starting from 33%, the fraction of cellulose (dry matter basis) decreased in all the storage systems tested, reaching 22% in ventilated bins, 18% in unventilated bins, and only 12% in open-air piles. However, the percentage variation of lignin and cellulose content can be misleading, because these values must be proportioned to the dry matter losses occurring during storage.

These experiences revealed in small scale that dry matter losses of chopped giant reed can be remarkably controlled by speeding up the drying process with forced ventilation systems. On the other hand, the climatic factors, even during the Italian dry season, can negatively influence the storage performance of the biomass if no drying methods are applied. Cellulose is the polymeric component that suffered most during storage, reducing significantly the bioenergy potential of the product (bioethanol and biogas production), in relation to the system used.

4.5.4 Biomass Pretreatment

Pretreatment aims to improve or modify the biomass characteristics in a way that allows or improves the efficiency of energy conversion. Pretreatment differs according to the conversion process and can be grouped in four main macrocategories: mechanical, thermal, chemical, and biological. In biomass combustion, the most critical factor affecting the efficiency of the process is the moisture content, which in turn influences in a negative way the heating value of the fuel and therefore the final energy yield of the process. To increase the efficiency of the conversion, thermal pretreatments such as forced drying or torrefaction can be applied to reduce the parameter and bring biomass to very low levels of moisture content. The main drawback of this method is the cost of the machinery, its maintenance, and the cost of the energy spent to dry the product. All these aspects make the breakeven period much longer and require higher initial investments. However, in recent years, the efficiency of these systems is increasing and technologies are making pretreatment more and more affordable (Fig. 4.15).

However, it should be pointed out that in the case of combustion, pretreatment is not mandatory, since occasional biomass management can provide natural drying over long periods. On the contrary, there are cases in which pretreatment is necessary, such as the biodegradation of cellulose. In fact, from a chemical point of view, lingocellulosic biomasses like that of giant reed have a complex and rigid cell structure, consisting of hemicellulose, cellulose, and lignin in variable proportions that mainly depend on cropping factors.

Figure 4.15 Mobile experimental drier tested at CREA-IT powered by a pellet boiler. © http://www.essiccatoremobile.it.

Lignin is the most recalcitrant component of biodegradation, also hampering cellulose biodegradability. To overcome this constraint, different pretreatment processes can be carried out to improve biomass degradability and facilitate lignin removal, hemicellulose solubilization, reduction of cellulose crystallization, and to increase the surface for enzymatic attack. In this case, pretreatment may consist of milling operations, thermal treatment (such as the use of liquid hot water), chemical treatment (such as acid or alkaline hydrolysis), and biological treatment based on enzymatic reactions (Raspolli et al., 2011).

4.6 Biomass Productivity and Uses

4.6.1 Productivity of Giant Reed Across Europe

Currently, giant reed is widely planted in East Asia, Mediterranean regions, and both East and West coasts of the United States. Giant reed production potential has been reported across the globe, with the majority of trials being located in Europe and the United States, although in the latter case giant reed is considered as an invasive plant in riparian environments (Lambert et al., 2014; Williams et al., 2009).

A wide range of yields is reported in the literature (Table 4.4), depending on the site, climate, soil type and fertility, inputs, cultivation and harvest practices, and age of plantation. *A. donax* can reach up to 98 Mg ha^{-1} yr^{-1} of dry matter from as early as the second growing period when grown under high water and nitrogen fertilization inputs (Borin et al., 2013), with growth rates of about 5 cm day^{-1} (Pilu et al., 2013). In Central Italy, a 10-year study showed a higher dry mass production rate of giant reed (37.7 ton yr^{-1} ha^{-1}) than that of miscanthus (28.7 Mg ha^{-1} yr^{-1}) (Angelini et al., 2009). Due to its high growth rate, giant reed can be harvested twice per year (harvest–regrow–harvest) producing 20% more biomass than that obtained from a single harvest (Ragaglini et al., 2014). On the opposite side, very low yields of 5.0 and 6.4 Mg DM ha^{-1} yr^{-1} of dry matter averaged over the first 4 years of growth are reported in trials carried out in marginal conditions with only residual fertility in the soil and no irrigation (Christou et al., 2015; Knoll et al., 2012).

Long-term data (Angelini et al., 2009; Christou et al., 2015; Monti and Zegada-Lizarazu 2016) showed that dry matter yields of giant reed reach a peak at the fourth year—or the fifth for increased nitrogen fertilization rates—and then follows a yield-decreasing phase. Longer-term data from the sixth and seventh years of growth showed yields of 36.5 and 27.3 Mg DM ha^{-1} yr^{-1} (Dragoni et al., 2015), 25.3 and 17.6 Mg ha^{-1} yr^{-1} in the 10th and 13th years of growth (Monti and Zegada-Lizarazu, 2016), while Christou et al. (2015) recorded yields of 12.3 Mg DM ha^{-1} yr^{-1} in marginal lands in the ninth growing season. In another study (Alexopoulou et al., 2015), the long-term yields (11–22 years) of switchgrass (*P. virgatum* L.), miscanthus (*M.* × *giganteus* Greef et Deuter), and giant reed (*A. donax* L.) grown in northern and southern Mediterranean environments are reported. Giant reed outperformed switchgrass in the northern Italy environment (21.2 and 13.6 Mg DM ha^{-1} for giant reed and switchgrass, respectively), whereas miscanthus showed intermediate production compared to giant reed and switchgrass.

Recorded yields were obtained from unimproved, wild populations of giant reed and by using conventional cultivation methods, thus future breeding efforts and optimized production methods will probably lead to an increase in biomass yields from *A. donax*.

4.6.2 Biomass Characterization

The attractive features of giant reed for bioenergy production are its yielding potential and growth rate, its tolerance to dry environments, and low-input cultivation. The fuel characteristics of the harvested material, such as calorific value, ash, volatiles, and fixed carbon content of stems, can be considered satisfactory for its energy use.

The dry matter content of *A. donax* L. grown in Mediterranean climates ranges from 36% to 57% (El Bassam, 1996; Christou et al., 2015; Dragoni et al., 2015). Dragoni et al. reported that dry matter content was higher in single harvests compared to double harvest systems.

The calorific value of giant reed is reported to range from 17 to 18.8 (Angelini et al., 2005; Ge et al., 2016). In an experiment carried out in Greece in the Bioenergy Chains Project (Christou et al., 2005) it was noticed that the calorific value of stems was characterized by low variation compared to leaves. More specifically, the recorded range for gross calorific value of manually harvested stems ranged from 18.2 to 19.1 MJ kg^{-1}, while for leaves it ranged from 17.2 to 19.8 MJ kg^{-1}. Irrigation and nitrogen fertilization had no clear effect on calorific value apart from irrigation on leaves where nonirrigated plants exhibited the highest calorific values. In a study conducted in Greece (own data), the calorific value of different aerial parts of a number of *A. donax* populations grown in Greece ranged from 17.3 to 18.8 MJ (stem) and 14.8 to 18.2 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).

Chemical analyses show a rather high ash content that ranges from 5.3% to 8.1% (Amaducci and Perego, 2015; Zegada-Lizarazu et al., 2010; Nassi o Di Nasso et al., 2010), depending on clones, year of plantation, and fertilization treatment. Nassi o Di Nasso et al. highlighted that ash content is higher in crops grown without fertilization and harvested in winter. Dragoni et al. reported lower values of 3.4% to 4.8% in single harvest systems compared to 4.7%–8.7% for double harvest systems within the year. It seems that double harvest decreases the fuel quality of the stems for thermochemical treatments. The high measured values for ash can be attributed to the contribution of leaves in the harvested material. Ash content was considerably higher in leaves than in stems, ranging from 5% to 11% depending on the irrigation and nitrogen fertilization combinations for leaves, and from 3% to 5% for stems (Christou et al., 2015). Nonirrigated plants resulted in slightly higher ash content in stems and lower ash content in leaves than the irrigated plants. Nitrogen fertilization differentiation had no clear effect on ash content. The rather high ash content found in giant reed samples indicates the probable need for automatic ash removal equipment in combustion systems. The later the harvest, the less leafy material in the harvested biomass and thus the lower ash content (Mantineo et al., 2009).

The stems of *A. donax* L. contain 43.4% cellulose, 25.1%–29.2% hemicellulose, and 6.9%–10.6% lignin, depending on different clones (Amaducci and Perego, 2015).

4.6.3 Biomass Uses

A. donax has played an important role in the civilization of the western world through its influence on the development of music, which can be traced back 5000 years. The pan pipe or syrinx was made from giant reed; Egyptians seemed to have used Arundo leaves to wrap mummies in the fourth century AD (Perdue, 1958). Because of the multiple uses of its stems the plant was intentionally distributed around the globe. It can be used for musical instruments, rayon, paper and pulp, particle boards, handwoven baskets, fishing rods, fencing, shading, ornamentals, etc. Perdue also reported that the rhizomes have been used as a sudorific, diuretic, and antilactant, and in the treatment of dropsy.

Giant reed has been examined as a feedstock for bioenergy production. In January 1997, a European "Giant Reed (*Arundo donax* L.) Network" was established to generate information on the potential of the plant for nonfood uses (energy, paper, and pulp). In 2005, a second network on "Bioenergy chains from perennial crops in South Europe" (www.cres.gr/bioenergy_chains) was set aiming to define and evaluate complete bioenergy chains from biomass production to thermochemical conversion for the production of valuable energy products. The whole supply chain, from feedstock sourcing to fuel production and product utilization, was developed in another EU project, BIOLYFE (www.biolyfe.eu), aiming to demonstrate an innovative technology for the production of second-generation bioethanol on a 40,000 ton/step scale. More than 25 ha of giant reed have been dedicated to specific trials and monitoring. From 2011 to 2015, the EU-funded project OPTIMA (www.optimafp7.eu) identified giant reed among the most high-yielding perennial grasses for the Mediterranean area, able to provide constant biomass supplies for energy and other plant-derived bioproducts.

Giant reed is also being researched as a possible replacement fuel source in a study run by Portland General Electric aimed at converting a coal-fired electric plant into a total biomass facility of 300 MW capacity (2.6 million MWh yr^{-1}) using torrefied giant reed (Lewis et al., 2012).

Furthermore, anaerobic digestion has been employed to produce biogas and biomethane, while a few studies have investigated fermenting giant reed for ethanol production.

Interest has also been put on the production of fuels, chemicals, and other products of high added value within a multiproduct biorefinery concept to ensure a sustainable transition from the petroleum-based to biobased economy. Giant reed was tested as a sustainably grown, low-input feedstock for the production of chemicals and advanced biofuels (www.eurobioref.org).

4.6.3.1 Thermochemical conversion tests

In the framework of the "Bioenergy chains from perennial crops in South Europe," giant reed was subjected to the following thermochemical conversion tests (Christou et al., 2005):

Combustion tests

A set of combustion tests was run at laboratory scale and in a 150 kW thermal KWB rotating grate furnace (Coulson et al., 2004; Dahl and Obernberger, 2004). At the laboratory scale, chopped giant reed at 6.9% ash content did not melt due largely to much lower combustion temperatures on the grate caused by bulk density and rate of heat release. At the pilot scale, giant reed at 6.13% ash content gave severe slagging in the primary combustion zone at 1000–1200°C. Similar results were taken with miscanthus and cardoon. High K and Cl gave high concentrations of KCl in the fly ash and high rates of fouling (likelihood of severe corrosion). Increased particulate emissions were also measured. The high volume of ash generated together with accumulation of slag on the grate limited operation to ~7 h before combustion performance deteriorated.

Pyrolysis tests

Fast pyrolysis tests have been performed at Aston using a small fluidized-bed reactor at temperatures between 425 and 550°C (Coulson et al., 2004; Coulson and Obernberger). For giant reed at 4.2% ash content, pyrolysis liquid yields were low due to the catalytic effect of the alkali metals. A maximum organic liquid yield of 47% on a dry ash free (daf) basis was measured; this compares to values of 60%–65% for wood feedstocks. Low oil yield was accompanied by high water content of the bio-oil and high gas and char yields. This bio-oil would be unacceptable as a fuel because of its low calorific value. Limited ash reduction by cold water washing was performed on the feedstock, reducing the ash content to 2.75% db (reducing K by over 55%). This led to an increase in organic liquids to 59% daf.

Gasification tests

Pilot-scale gasification tests have been carried out by BTG on a selected fluidized-bed gasifier to permit accurate control of temperature and minimize feedstock preparation requirements (limited size reduction using hummer mill). When using giant reed the unit was operated without problems at temperatures of 700–750°C, i.e., well below the minimum observed Initial Deformation Temperature of 1030°C. Tests on giant reed revealed much higher heating value of the produced gas and very high tar content.

4.6.3.2 Biogas/Biomethane

Giant reed has generated wide interest for biogas/biomethane production, substituting maize, which is a food crop and as such cannot be used for energy purposes. On the contrary, giant reed is considered as a low-input crop, able to be grown in arid and marginal lands and is a very high-yielding crop for Mediterranean environments. Ragaglini et al. (2014) calculated the highest biochemical methane potential of giant reed at 392 L kg^{-1} VS (volatile solids), which is equivalent to a methane yield of 11,585–12,981 m^3 ha^{-1} for a biomass yield of 35–40 Mg ha^{-1}, which was achieved with a double harvest of the crop in the same season. These methane yields exceeded the methane produced with a single harvest of the crop at the end of the growing season by 35%.

Several pretreatment processes were studied aimed at increasing methane yields of giant reed. Di Girolamo et al. (2013) reported a potential CH_4 yield of 273 L kg^{-1} VS from untreated giant reed biomass, which showed a 23% increase in methane yield after pretreatment at 180°C for 10 min. Pretreatments with H_2SO_4 as a catalyst exhibited a strong methanogenic inhibition (Di Girolamo et al., 2013), whereas alkaline pretreatment significantly increased cumulative methane yield (by 63%) over that of untreated biomass (217 L kg^{-1} VS) (Jiang et al., 2016). Increasing total solids (TS) from 8% to 38% decreased methane yield but at 20%–23% TS the maximum volumetric methane production was obtained (Yang and Li, 2014).

Ensilage was more suitable than fungal pretreatment for giant reed storage and digestibility (Liu, 2016a,b,c). Ensilaged giant reed with the addition of urea achieved a cumulative methane yield of 173 L kg^{-1} VS, which was 18% higher than that of fresh giant reed (Liu et al., 2015), due to the production of organic acids and ethanol during ensilage. Ensilaged giant reed and maize were tested in mixtures with pig slurry for biomethane production by Corno et al. (2015) and results indicated that giant reed produced less biomethane than maize, $174 \pm 10\,Nm^3\,CH_4\,Mg^{-1}\,TS^{-1}$ and $245 \pm 26\,Nm^3\,CH_4\,Mg^{-1}\,TS^{-1}$, respectively. However, the biomethane produced per unit of land was higher for giant reed than for maize (12,292 $Nm^3\,CH_4\,ha^{-1}$ and 4549 $Nm^3\,CH_4\,ha^{-1}$, respectively) because of its high biomass yields.

4.6.3.3 Paper and Pulp

Giant reed is primarily used as a fiber source for paper and pulp (Shatalov and Pereira, 2002, 2005, 2006; 2007, 2008) and making chipboard panels (Flores et al., 2011).

Comprehensive research on the suitability of *A. donax* for paper pulp production revealed that pulp quality was strongly influenced by plant morphology; the leaves cause a significant decrease in pulp yield when cooked with stems, whereas stems can also cause a different access to pulping. More particularly, the internodes of the stems of *A. donax* are more suitable for pulping, and the presence of nodes has an adverse effect on pulp yield and properties (Shatalov and Pereira, 2002; Ververis et al., 2004). Pulps with higher screened yield (44.5% vs. 38.6%) and lower content of residual lignin (Kappa number 25 vs. 33) were produced from internodes compared to nodes (Shatalov and Pereira, 2002). Papermaking properties as well as brightness of unbeaten Kraft pulps from internodes were also higher (burst index 0.7 vs. 0.2 $kPa\,m^2\,g^{-1}$, tensile index 25.2 vs. 5.2 $Nm\,g^{-1}$, tear index 13.3 vs. 4.4 $mN\,m^2\,g^{-1}$, and brightness 23.9 vs. 21.2% ISO for pulps from internodes and nodes, respectively) (Shatalov and Pereira, 2002). The unsuitability of nodes is attributed to their anatomical structure, namely, the predominance of the nonfibrous short-cell tissues in the nodal diaphragm. This negative impact can be minimized using adequate screening techniques to remove nodes from the crushed stems before pulping. Furthermore, due to the higher proportion of internodes in the stems, the results for whole-stem Kraft pulping are expected to be similar or somewhat lower than for internodes.

Between the two tested pulping methods (Kraft and organosolv), the organosolv process, which is an environmentally friendly technology, showed a greater potential to produce high-quality nonwood fibers (Shatalov and Pereira, 2005, 2006, 2007, 2008). The papermaking properties of unbeaten organosolv pulps were higher than those for Kraft pulp and furthermore some properties were higher than Kraft pulp from *Eucalyptus globulus* wood. All organosolv pulps were characterized by high viscosity and brightness, suggesting good bleachability. Further studies on several pretreatments of giant reed organosolv pulps indicated that xylanase bleach boosting (Shatalov and Pereira, 2007) and ozone-based totally chlorine-free bleaching (Shatalov and Pereira, 2008) substantially improved the bleaching of organosolv pulps.

In addition, sulfur-free cellulosic pulps were produced from giant reed stems after selective removal of hemicelluloses by dilute sulfuric acid hydrolysis following a biorefinery scheme (Shatalov and Pereira, 2013).

4.6.3.4 Other Uses

Giant reed was proven unsuitable for the production of hydrogen (through combined dark fermentation combined with anaerobic digestion systems and photofermentation) (Corneli et al., 2016a,b), because stems are rich in fiber, which is slowly degraded and has low initial volatile fatty acid concentrations.

A few studies have investigated fermenting giant reed for ethanol production. Dilute-oxalic acid pretreatment of giant reed at different concentrations, temperature, and reaction times, followed by coupled saccharification and fermentation of the solid fraction with several yeast strains, can be considered a promising methodology for second-generation bioethanol production (Scordia et al., 2012, 2013).

The concept of simultaneous saccharification and fermentation was also proved by Lemons e Silva et al. (2015). Diluted acid and alkaline pretreatment of giant reed stems followed by enzymatic hydrolysis reached 42 g/L of glucose, a partially delignified material, which was further subjected to a simultaneous saccharification and fermentation process. The fermentability of the pretreated biomass was performed successfully and resulted in approximately 75 L of ethanol per ton of cellulose.

The solid cellulosic residue of giant reed after low-temperature dilute sulfuric acid hydrolysis can be easy converted to fermentable sugars (glucose) by enzymatic saccharification, providing cellulose digestibility of 70% versus 9% for untreated biomass, according to Shatalov and Pereira (2012).

Investigations on the possibility of using *A. donax* L. for bio-oil or chemicals by subjecting it to supercritical and catalytic fluid extraction using organic solvents with and without catalysts at different temperatures had shown that *A. donax* L. was a liquefiable feedstock. 2-Butanol and acetone as solvents and sodium hydroxide as catalyst provided the optimum conditions for liquefaction (Aysu and Küçük, 2013). Giant reed was also used as a raw material for manufacturing activated carbon (Sun et al., 2012).

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Reed Canary Grass: From Production to End Use

5

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5.1 Introduction

Reed canary grass (*Phalaris arundinacea* L.—RCG) is a lignocellulosic perennial crop that is carbon efficient, in terms of sequestration and nutrient recycling, and grows well on land that is marginal for food and feed production (Pahkala et al., 2008; Wrobel et al., 2009). It can therefore help deliver sustainable bioenergy without impacting food security. RCG exhibits a unique combination of characteristics including:

1. It is a native species in Europe, Asia, and North America (although the native North American type is very rare; Jakubowski et al., 2014), with carbon sink and biodiversity benefits.
2. It is inexpensive to establish and fits existing farming practice, providing flexibility and low risk to farmers.
3. It is able to produce harvested biomass from late summer until early spring thereby producing biomass earlier in the year than other energy grasses, thus reducing storage requirements for end users.
4. The low cost of establishment and faster rates of return on financial investment make RCG a good crop for farmers to grow to gain confidence in farming for energy.
5. It tolerates a wide range of management practices that include grazing or conservation harvesting (on a frequent or infrequent basis). As such, its use in agricultural systems is highly varied, including for pasture, hay or silage production, straw or bedding for livestock, pulp and paper, soil conservation, and biomass for conversion to bioenergy, biomaterials, or as a feedstock for industrial biotechnology.

Although relatively limited in its cultivation to date, RCG offers considerable potential as a bioenergy crop, especially on marginal land, as it can grow well in both dry and wet areas. For example, RCG is a widely adapted temperate grass and broadly tolerant of many stresses including flooding, drought, freezing, and grazing. As such, it can be found in a wide array of habitats, including wetlands, riparian zones, stream banks, irrigation channels, roadsides, forest margins, pastures, and disturbed areas (Casler et al., 2009). RCG grows extremely well in wet soils, withstanding flooding for long periods across a wide pH range from 4.9 to 8.2 (Bittman et al., 1988; Carlson et al., 1996). It also exhibits excellent drought tolerance. This facilitates harvesting

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and makes it relatively more productive in the summer compared to many other cool season/temperate grass species (Carlson et al., 1996). The opportunity to produce biomass in late summer, the ability to tolerate a wide range of environmental stresses, management practices, and growth on very marginal land (including brownfield sites), and the flexibility to use the crop as an animal feed as well as a fuel mean that RCG has an important role to play in the mix of energy crops grown in multiple geographies.

RCG is already used as an energy crop in Nordic countries (approximately 20,000 ha; Don et al., 2012) and trials by Teagasc have shown that it can produce good biomass yields on mineral soils in a warm, temperate, Atlantic climate (Finnan, 2010) in Ireland. However, despite the opportunities, RCG has received limited attention by plant breeders to date and is still largely undomesticated.

Historically, the earliest report of RCG seed being sold was for use as forage in 1836 in Hamburg, Germany, while the first agronomic trials began in 1837 at the Swedish Agricultural College (Alway, 1931). The earliest known reports of intentional breeding were in the early 20th century in North America, but its use for 100 years before this in Europe likely resulted in both intentional and unintentional mixing and selection of germplasm (Casler, 2010). Current cultivars of RCG were developed for use with livestock or soil conservation applications (Casler, 2010), but newer cultivars are being developed for the bioenergy market, and present a new opportunity to optimize this versatile crop as an industrial crop. The history of cultivation over several centuries means that lack of agronomic knowledge or advice should not be a barrier to adoption (Glithero et al., 2013).

5.2 Genetics and Breeding

Native North American types have been verified by forensic DNA analysis, in comparison to herbarium samples collected in remote regions of the Pacific Northwest United States in the early 19th century, before European immigrants settled that region (Jakubowski et al., 2013, 2014). European and North American RCG herbarium samples are largely indistinguishable from each other on a phenotypic basis, indicating that European and North American strains represent different populations or races of the species.

RCG genotypes differ in their ability to survive extreme cold in direct proportion to their latitude of origin and mean winter temperature at their point of origin (Klebesadel and Dofing, 1990). So far, no data exist on phenotypic performance of native North American genotypes—all existing cultivars trace to European races of the species.

5.2.1 Taxonomy and Genetics

RCG has two chromosome races: tetraploid ($2n=4\times=28$) and hexaploid ($2n=6\times=42$) (Anderson, 1961). The tetraploid race originated in the cool temperate zone of Europe and spread into Asia and North America prior to recorded history. The hexaploid race is largely restricted to the Iberian Peninsula and may be derived from an interspecific hybrid between *P. arundinacea* and *Phalaris aquatica* L. (Jakubowski et al., 2011; McWilliam and Neal-Smith, 1962).

RCG is wind pollinated, with a strong self-incompatibility system that promotes a high degree of cross-pollination (Carlson et al., 1996). As such, individual populations are highly variable, demonstrating large amounts of genotypic and phenotypic variability (Casler et al., 2009; Jakubowski et al., 2014; Marum et al., 1979a). DNA marker analyses of Eurasian accessions has revealed at least six subpopulations with some geographic clustering but considerable admixture, indicating the strong influence of human-induced migration (Jakubowski et al., 2011). Eurasian populations are genetically distinct from North American native populations, which appear to have been derived from postglacial migration across the Bering Strait (Jakubowski et al., 2014).

5.2.2 Breeding and Selection History

Breeding objectives for RCG have historically focused on solving problems associated with its use in agriculture. Seedling vigor and establishment capacity, seed retention, and alkaloid profiles have served as the most important traits in breeding programs for the past 50 years (Casler, 2010). One of the two most significant advancements has been the breakthrough in improved seed retention, following interspecific hybridization with *P. aquatica* and backcrossing to RCG (Oram and Lodge, 2003). Ironically, these interspecific hybrids have allowed the transfer of aluminum and acid-soil tolerance from RCG into *P. aquatica* (Ridley et al., 2002).

RCG possesses considerable genetic variability for alkaloids (tryptamines, β-carbolines, and gramine). Alkaloids are a strong antiquality and antiherbivory defense mechanism in RCG, suppressing palatability, intake, and live weight gains of ruminant livestock (Marten, 1985, 1989; Wittenberg et al., 1992). The occurrence of tryptamines and β-carbolines is governed by a simple two-locus genetic model, so their elimination can be accomplished relatively simply in a single generation with the use of a simple qualitative spectrophotometric assay (Marum et al., 1979b). While gramine has not been entirely eliminated from any known RCG genotypes, reductions in gramine concentration have been shown to lead to significant increases in ruminant live weight gains (Marten, 1985, 1989; Wittenberg et al., 1992). Low-alkaloid cultivars have become so dominant in the marketplace that old cultivars with tryptamines and β-carbolines in their herbage have been discontinued and many can only be found in gene banks.

Because alkaloids function to protect plants from insect predation and some environmental stresses, the use of genotypes with "wild-type" high alkaloid profiles could be a necessity for developing dedicated bioenergy feedstocks. RCG genotypes with high alkaloid concentrations are more resistant to infestation by stem borers such as frit fly, *Oscinella frit* (Byers and Sherwood, 1979), and since gramine is also a deterrent to aphid feeding in barley (Corcuera, 1993), alkaloids may well act as a mechanism of antibiosis to multiple families of insects.

5.2.3 Prospects on Breeding for Biomass Production and Conversion

Existing cultivars of RCG are suboptimal for the development and production of dedicated bioenergy feedstocks due to lower yield and pest resistance in low-alkaloid germplasm. The discovery, collection, evaluation, and refinement of new sources of germplasm suitable for bioenergy feedstock production are therefore necessary. Relatively modest exploration trips to acquire new accessions in Canada, the United States, and northern Europe have demonstrated a clear potential for significant increases in biomass yield potential (Casler et al., 2009; Lindvall, 1997; Olsson, 1999; Sahramaa, 2003, 2004; Sachs and Coulman, 1983). Many of these accessions demonstrated immediate superiority over existing cultivars with relatively little effort from breeding and selection.

There is also a large amount of genetic variation for biomass quality traits that could be used to select cultivars with improved conversion efficiency (Olmstead et al., 2013; Marum et al., 1979a). Breeding objectives and selection criteria will likely depend on the conversion platform, e.g., reduced lignification or reduced cross-linking between lignin and cell-wall polysaccharides for fermentation (Casler et al., 2008), reduced Si, Cl, and K combined with lodging resistance for combustion (Lindvall, 1997), or simply high biomass yield for thermochemical conversion (Boateng et al., 2008). Sahramaa et al. (2003) have shown that improvement of biomass yield for a one-harvest management system should focus on tall plants with many nodes and a high straw fraction, high panicle number, reduced leaf area index, and reduced axillary shoot development, demonstrating a clear deviation from long-term breeding objectives for livestock agriculture.

A recent ERA-NET (European Research Area, EU funded) Bioenergy project “Optimisation of Reed Canary Grass as a Native European Energy Crop” (ORNATE) involving collaboration between the United Kingdom and Sweden has investigated how accessions can be matched to diverse environments and uses, and the tools and germplasm to drive a state-of-the-art breeding program. In the United Kingdom, the highest yielding population (Bs5321) was derived from six plants from each of four local accessions (between and within selection) used to create a synthetic variety. Phenotypic imaging was successfully used to record plant height, leaf area, and water usage. One-meter pipes were used to measure drought resistance, and marker-assisted selection is being developed.

5.3 Production, Harvesting, and Economics

Biomass from RCG can be utilized in a range of energy conversion processes, including combustion (Hadders and Olsson, 1997; Landström et al., 1996; Christian et al., 2006; Pahkala et al., 2008), anaerobic digestion (for biogas) (Geber, 2002; Butkutė et al., 2014; Kandel et al., 2013b), pyrolysis (Boateng et al., 2006), and cellulosic ethanol production (Dien et al., 2006; Digman et al., 2010). The intended end use of the biomass influences the approach needed for production and harvesting. For instance, when used for forage or biogas production the crop will be harvested green and thus will require higher fertilizer input. For biomass production, however, delaying harvest until the spring following the growing season minimizes the nutrient requirements of the succeeding crop because nutrients are translocated from the shoots to the rhizomes system over the fall/winter period before being remobilized to the new shoots in the following spring (Partala et al., 2001). This late harvest results in lower moisture, ash, potassium, and chloride content of the harvested biomass (Landström et al., 1996; Hadders and Olsson, 1997).

5.3.1 Establishment

RCG has low set-up costs as it is established from seed (Lewandowski et al., 2003) that can be drilled, broadcast (Brann, 1998), or established by no-till techniques (Leep et al., 2003). Establishment can be impaired by low seeding vigor (Casler and Undersander, 2006), although selection for greater establishment capacity can mitigate against this characteristic. Seeds require several days at a cool temperature to germinate, and are very sensitive to competition (USDA, 2002). Morrison and Molofsky (1998) reported that RCG seedlings are more sensitive to interspecific competition than to abiotic stress.

Seeding rates of 6–9 kg ha^{-1} are recommended for forage production (Bittman et al., 1988), while higher seeding rates ranging from 11 to 20 kg ha^{-1} have been used for bioenergy production (Lewandowski et al., 2003; Lindvall et al., 2015; Pahkala, 2007). However, increased seeding rates have been found to have little effect on short-term establishment of RCG under competitive conditions (Casler et al., 1999).

Although sowing can take place in spring or fall, higher yields have been measured after sowing in May–June rather than September (Saijonkari-Pahkala, 2001). Sowing is typically followed by rolling, to conserve moisture in the seedbed (Lewandowski et al., 2003), and by the application of a broadleaf herbicide (Christian et al., 2006; Pahkala, 2007).

5.3.2 Fertilization

RCG has been reported as very responsive to nitrogen (N) fertilization (Wrobel et al., 2009), although optimal levels will naturally vary according to soil status, and the timing of harvest will significantly affect nutrient remobilization. As mentioned earlier, harvesting in spring will allow the remobilization of nutrients to the underground rhizome, thus improving sustainability and quality. Many studies that have investigated the effect of N addition were conducted when the crop was harvested green for forage, therefore requiring additional N (for instance, Cherney et al., 2003). Reports regarding the response of RCG to N fertilization when harvested in the spring are rather contrasting. Landström (1999) found no yield response to N fertilization above 100 kg N ha^{-1}, with an economic optimum around 70 kg N ha^{-1}. Lindvall (2015) found only small and mostly insignificant yield decreases at three fertile sites when N fertilization was halved, compared to recommended fertilization of 40–100 to 80–60 kg ha^{-1} in consecutive years. Kätterer et al. (1998) found no response of RCG to added N, and Smith and Slater (2010) found no significant effect of the addition of a range of organic and inorganic fertilizers with N contents up to 87.5 kg N ha^{-1} on the yield of field-grown RCG. Lewandowski and Schmidt (2006), however, observed that biomass yield in RCG *increased* with N supply *up to at least* 163 kg N ha^{-1} in a study in Germany, but with an associated *decrease* in N use efficiency (NUE). This study highlights the importance of taking into account measures of NUE and other energy inputs, as well as evaluating the energy yield of the crop and efficient utilization of the land available. However, with respect to the yield response of RCG to N fertilizer, the authors point out that the study was performed over different locations with correspondingly different photoperiods, and RCG at some locations did not flower. Flowering time has been shown to impact biomass yield and quality (Jensen et al., 2017) in diverse *Miscanthus* genotypes, where earlier flowering genotypes showed improved combustion qualities, most likely due to a more thorough remobilization of nutrients following the physiological processes of flowering and senescence. It is therefore necessary to consider the suitability of genotypes, influenced at least in part by their origin, to different locations. More work is needed in this area to help identify optimum ideotypes for diverse environments. Determination of energy inputs versus energy outputs is essential for the maximization of sustainable high yields.

Alternate fertilizer treatments can also be considered: Lindvall et al. (2015) reported that yield was not reduced when ash derived from combusted RCG replaced P fertilizer. However, ash from co-combustion with waste should be avoided due to high heavy metal content. Organic wastes have also successfully been used to fertilize RCG crops (Schmitt et al., 1999; Lamb et al., 2005), and Kołodziej et al. (2016) reported a peak in RCG yields with an application of 40 t ha^{-1} of municipal sewage sludge. There has been substantial resistance among Swedish farmers to the use of sewage sludge in fields used for food and feed production (Lindvall et al., 2012), however, but this option should be considered afresh for energy production.

5.3.3 Biomass Production

RCG can produce high yields of biomass under proper management conditions (Wrobel et al., 2009). Reported yields are quite contrasting, but of course will vary with multiple factors, including cultivar used (different cultivars, mostly optimized for forage, rather than bioenergy, production), environment (including temperature, rainfall, solar radiation, and photoperiod (see earlier)), fertilization (see earlier), and timing of harvest. Delayed harvests reduce dry matter (DM) yield due to the loss of leaves and pieces of stem over the winter period, and yield losses of 24% have been reported when harvest was delayed from late December/early January to late January/early February (Christian et al., 2006). Yields of up to 12 t DM ha^{-1} were reported by Lewandowski and Schmidt (2006) for RCG grown in Germany and harvested in December, while Kołodziej et al. (2016) reported yields of up to 21.5 t DM ha^{-1} following the use of sewage sludge, with an October harvest, although in subsequent years yields were lower. Another way of maximizing yield, which also provides multiple outlets for biomass produced, may be to use repeat harvests. Tahir et al. (2011) and Shinners et al. (2010) found that two-cut systems produced more biomass than a single-cut system. Butkutė et al. (2014) reported yields of 12.8 t DM ha^{-1} using a three-cut system for anaerobic digestion. Whatever system is used, the energy input/output ratio must be considered to maximize sustainability.

Soil type also influences yield, and as may be expected, reported RCG yields were higher on organic and humus-rich soils compared to mineral soils, and on those with less than 15% of clay compared with clay soils (Heinsoo et al., 2011; Landström et al., 1996; Pahkala, 2007). Here, however, the best use of available land must be considered. Since RCG is known to tolerate a range of conditions, as well as marginal land, the best use of RCG as an energy crop may be to grow it in areas less suitable for other crops.

5.3.4 Harvesting

RCG can be harvested with conventional agricultural machinery, irrespective of whether it is grown for combustion or for other uses such as biogas production. Mowing and baling systems are typically used to harvest RCG when the crop is intended for utilization as a combustion fuel, but harvest losses can be high (Pahkala, 2007). Losses can be minimized by the use of machinery combinations. In Finland the use of disc mowers without conditioners, followed by swathing with a rotary rake, reduced harvest losses compared to the use of mowers with conditioners (Pahkala et al., 2008). In one study the cheapest harvest technique was to handle the biomass as loose chopped grass, picked up by a forage wagon and reloaded to a crane truck for transport to the end user. The most efficient compaction method was by using large square bales (Örberg, 2010). DM yield decreases with cutting height, and is maximized at a low cutting height of 3.8 cm (Lawrence and Ashford, 1969). However, such a low cutting height can predispose the crop to winter injury.

Shinners et al. (2010) reported that the average bale density (163 kg DM m^{-3}) was unaffected by the type of wrap (twine/netting) and that DM losses in bales stored outside could be minimized by wrapping the bales in plastic or breathable film.

5.3.5 Economics

Relatively few studies have been conducted on the economics of RCG production and studies are difficult to compare as they were performed in different countries at different times and used different assumptions on costs, yields, and the price of biomass. The least profitable year in the plantation life cycle is the establishment year in which the cost of establishment is not balanced by revenue from biomass production (Riche, 2005). Costs calculated over the life cycle of the crop are influenced by the persistence of the crop and the interval between successive sowing operations. The cost of production falls with increasing yield. For example, Brummer et al. (2002) calculated that the production cost of RCG at 7.41 t DM ha^{-1} was US\$79.89 t^{-1}, which fell to US\$49.88 t^{-1} when yields reached 14.83 t DM ha^{-1}. Riche (2005) calculated an average gross margin of £153.89 ha^{-1} for RCG grown at several sites across the United Kingdom. Across these sites, gross margins ranged from a minimum of £110.60 ha^{-1} to a maximum of £219.40 ha^{-1}. This variation in gross margins was largely the result of yield variation across different sites, although gross margin is also influenced by the price offered for the biomass.

In Sweden, RCG has not been able to compete with forest fuels in combined heat and electricity plants. The mean yield for spring-harvested RCG in a project with 45 farmers in northern Sweden was 4.2–4.9 t DM ha^{-1}, with an energy content of 4000–4800 MW ha^{-1}. A shortage of straw for bedding in regions with little grain production has made it more profitable to sell the grass for bedding than as a fuel (Bioenergigårdar, 2011). The official Swedish cost calculation, with all machine costs and wages for work conducted by the farmer included, for growing RCG at 4 t DM ha^{-1} is 4730 SEK ha^{-1}. In this study, establishment costs were allocated to 10 harvest years (Rosenqvist, 2017). The calculated income from selling the crop as fuel was only 3076 SEK ha^{-1} with the current low fuel price in Sweden. EU subsidies were not included in the income. If machine and labor costs can be cut in half by use of machines already available for other purposes, the net result can become positive also on marginal land (Rosenqvist et al., 2014).

5.4 Biomass Characterization

5.4.1 Physical Properties

The physical characteristics of RCG will vary significantly depending on factors such as genotype, growing conditions, and time of harvest. As stated, harvesting in spring improves fuel quality and allows dry harvesting (>80% DM) and access for machinery in northern Europe (Lewandowski et al., 2003). However, the timing of harvest should occur, where soil and weather conditions permit, before the emergence of the new season's growth, otherwise there will be a negative influence on combustion quality, and subsequent growth and sustainability. After senescence the bulk of the spring-harvested crop comprises upright, flexible, hollow stems, which are typically 2 m high and taper to c. 5 mm in diameter. Some leaves may remain attached to the stem at harvest, even after overwintering, and, unlike *Miscanthus*, RCG does not usually form a noticeable layer of leaf litter, although snowfall may cause extensive lodging in winter (Lötjönen and Laitinen, 2009). Cutting and baling the crop without chopping will result in the biomass having a fibrous, stranded texture that is bulky and therefore may be problematic for auger-fed combustion systems. If the biomass is densified by pelletization or briquetting then this risk is eliminated as it is likely to have required shredding and grinding, or milling, to reduce the particle size to <3 mm (Paulrud and Nilsson, 2001). Any additional processing, however, requires consideration of the energy input/output balance.

Harvesting during active growth stages is preferable for anaerobic digestion (Kandel et al., 2013b), in which case seed heads and/or leaves may accompany fibrous stems (Fig. 5.1B). Mowing, drying and baling, direct baling, wrapping, or loose harvesting with a forager are all possible. Wet storage directly after harvesting is preferable for liquid phase bioethanol or biorefinery applications (Digman et al., 2010). Typical water contents at harvest are 10%–20% after senescence or 50%–60% if cut when actively growing. Fig. 5.1C illustrates different physiology in the crop when different harvest times are used. Densities range from 70 kg DM m^{-3} for loose chopped biomass to 130–150 kg DM m^{-3} for round bales, and 170–200 kg DM m^{-3} for large square bales (Lötjönen and Laitinen, 2009).

The fibrous properties of RCG have potential use in printing paper, specifically as short-fiber feedstocks to replace hardwoods such as birch, in Scandinavia and Canada

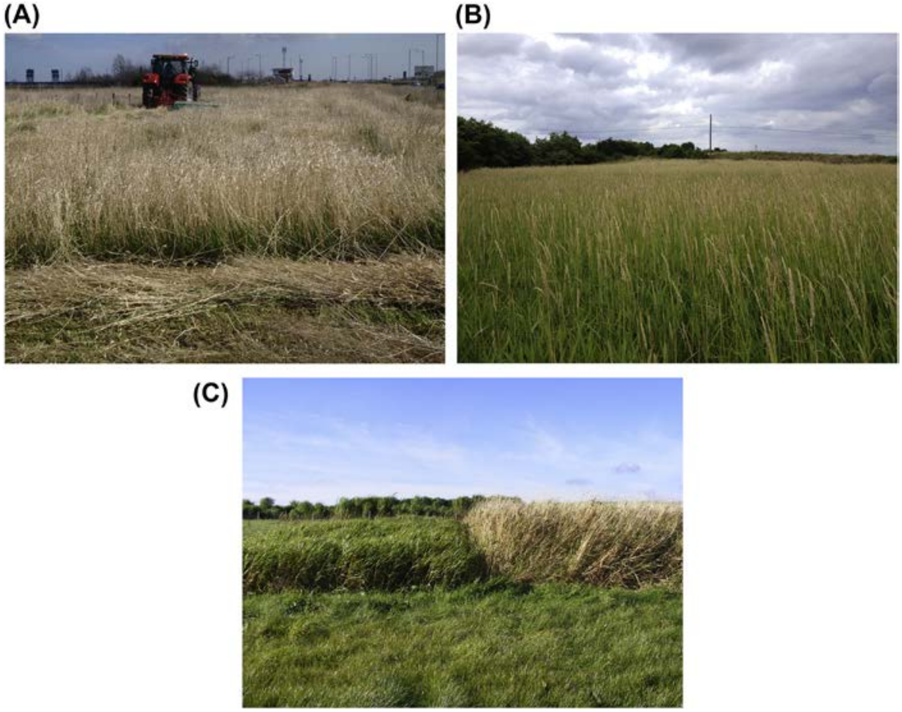

Figure 5.1 Character of reed canary grass (RCG) at different growth stages and harvesting for different purposes. (A) Overwintered RCG cut in spring (March 31, 2009) for combustion (note spring growth had recommenced). (B) Mature RCG with seed heads in late summer. (C) Summer regrowth of RCG following a June harvest for anaerobic digestion (*left-hand side*) next to RCG that has been left for a spring harvest (*right-hand side*) (August 30, 2017).

(Thykesson et al., 1998). Dry fractionation allows the mechanical removal of leaf material to reduce the undesirable inorganic component, while briquetting increases transportation efficiencies, resulting in a more sustainable alternative than direct transportation of birch logs (Finell et al., 2002; Finell and Nilsson, 2004).

5.4.2 Chemical Composition

The two most salient features of RCG biomass compositions are the relatively high ash and alkali metal contents, which are closely related and have implications for fuel quality and may limit their use in combustion systems (Table 5.1). As discussed previously, harvesting material in spring, where regrowth has started, will influence biomass composition, as was likely the case for material detailed in Table 5.1. Reported ash contents of the biomass also have a wide range at 1.9%–11.5% of DM, as do the respective contents of K (0.06%–0.81%), Si (0.56%–3.7%), and Cl (0.01%–0.30%). Ash fusion temperatures can range from 1100 to 1650°C (Lewandowski et al., 2003). Ash contents in RCG are strongly correlated with Si, which can comprise up to 85%

Table 5.1 **Representative fuel analyses of reed canary grass (RCG) from two agricultural sites (Sites 1 and 2), the average of four brownfield demonstration sites mechanically harvested in spring (Bales I) or the fall (Bales II), and two from a contaminated site (Site 3(a) and (b)) (Lord et al., 2008; Lord, 2015)**

	Site 1	Site 2	Bales I ($n=4$)	Bales II ($n=4$)	Site 3(a)	Site 3(b)
Fuel analysis (dry)						
Ash content, %	6.7	5.6	10.0	10.6	7.3	6.7
Volatile matter, %	77.0	79.9	72.1	71.9	74.6	78.0
Fixed carbon, %	16.3	14.5	17.9	17.6	18.1	15.3
Total sulfur, %	0.08	0.06	0.15	0.21	0.14	0.08
Chlorine, %	0.25	0.69	0.21	0.52	0.01	0.31
Carbon, %	42.5	40.3	37.6	45.2	45.4	41.9
Hydrogen, %	6.11	5.96	5.80	5.42	4.83	6.23
Nitrogen, %	1.78	1.14	1.00	0.99	0.32	1.60
Oxygen by difference, %	42.6	46.2	45.2	37.1	42.0	43.2
Gross calorific value, MJ kg^{-1}	18.383	18.483	17.924	17.734	19.606	18.844
Fluorine, ppm	220	220	15	15.1	28	230
Trace elements						
Cadmium, mg kg^{-1}	0.05	<0.05	0.05	0.05	0.31	0.05
Zinc, mg kg^{-1}	54.7	27.7	32.2	27.7	80.3	100.6
Vanadium, mg kg^{-1}	0.13	0.11	2.47	0.62	1.02	0.47
Lead, mg kg^{-1}	0.40	<0.3	3.76	0.79	4.74	2.08
Copper, mg kg^{-1}	3.22	2.52	6.09	4.28	6.42	5.83
Chromium, mg kg^{-1}	0.34	0.28	1.88	0.67	1.10	0.47
Nickel, mg kg^{-1}	0.47	0.34	1.70	0.59	1.24	0.54
Cobalt, mg kg^{-1}	0.10	<0.1	1.10	0.42	0.26	0.13
Tin, mg kg^{-1}	0.20	<0.2	1.19	0.10	0.43	0.20
Arsenic, mg kg^{-1}	0.10	<0.1	0.50	0.50	0.50	0.10
Mercury, mg kg^{-1}	0.02	<0.02	0.02	0.02	0.02	0.02
Boron, mg kg^{-1}	10.0	<10	9.1	8.5	10.0	10.0
Selenium, mg kg^{-1}	0.10	<0.1	0.50	2.36	0.07	0.10
Ash analysis						
SiO_2, %	84.0	83.0	61.9	61.5	78.2	83.4
$A1_2O_3$, %	0.50	0.44	2.67	0.74	1.85	1.08
Fe_2O_3, %	0.26	0.24	1.58	0.49	1.29	0.69
TiO_2, %	0.02	0.01	0.16	0.05	0.12	0.06
Mn_3O_4, %	0.05	0.05	0.11	0.08	0.11	0.06
CaO, %	4.19	4.24	9.47	9.30	6.84	5.12
MgO, %	2.13	2.37	3.26	4.17	2.48	2.09
Na_2O, %	0.45	0.49	0.76	0.37	1.24	0.40
K_2O, %	3.38	4.15	12.3	14.1	2.34	2.44
P_2O_5, %	3.79	4.25	6.64	6.37	4.07	3.85
SO_3, %	1.22	0.77	1.24	2.93	1.49	0.85

of the inorganic content and are higher when grown on clay soils compared to sandy or organic substrates (Burvall, 1997; Wrobel et al., 2009). Both ash and alkali contents, together with Cl and S, are reduced by delayed harvesting, which improves fuel quality by reducing the potential for fouling and increasing ash fusion temperatures. Ash melting behavior studies and comparisons with ternary phase diagrams suggest that higher ash contents lead to extended melting intervals and higher final temperatures for Si-rich ashes (Paulrud et al., 2001; Lord, 2015).

Gross calorific values for RCG would be broadly similar to other lignocellulosic biomass, other than for the diluting effect of the relatively higher ash contents, whereas the much lower water contents that are achievable at harvest mean that net calorific values (heating values) can be higher than for woody biomass, at 16.6–19.3 MJ kg^{-1} (Lewandowski et al., 2003). Torrefaction at 290°C increases the energy density of RCG by 12%, raising the higher heating value to 21.8 MJ kg^{-1} (on a dry ash-free basis) while reducing moisture content and enhancing combustion properties (Bridgeman et al., 2008). This is at the expense of reductions in the mass and energy yields, however, to 61.5% and 69%, respectively. Heating values of up to 27–28 MJ kg^{-1} have been reported for RCG char following pyrolysis at 400–500°C (Rafizan and Daud, 2015). In contrast, gasification of RCG at 600–1050°C produces noncondensable gas with an average calorific value of 13.6 MJ kg^{-1}, some 75% of that of the original biomass. Higher gas yields will be possible for RCG when harvested at the vegetative stage compared to the mature flowering stage (Boateng et al., 2006).

Until recently the biorefinery feedstock potential of RCG was perhaps less well known than its combustion and pyrolysis chemistry properties. However, the relatively low levels of lignin (19.4% DM) compared to cellulose or hemicellulose in delayed-harvest RCG, as indicated by glucose, xylose, and other extractable sugars from strong acid hydrolysis (67.42% DM), are indicative of the potential of RCG as a fermentation feedstock for bioethanol (Finell et al., 2011). Moreover, RCG shows superior bioethanol conversion potential compared to switchgrass after pretreatment and ensiling (Digman et al., 2010), with overwintered spring harvest material apparently more amenable to hydrolysis than that cut in the fall (Kallioinen et al., 2012). For anaerobic digestion, very similar levels of lignin were found in summer-harvested material just before and after flowering (19.3% and 20.4% DM, respectively) with broadly similar volatile solids (VS) contents (93% and 96%, respectively), but increases in total specific methane yields (0.34–0.43 m^3 CH_4 kg^{-1} VS) (Lehtomäki et al., 2008). When combined with the effects of higher total solids (i.e., lower water content) in the later-harvested material (from 20.2% to 29.5% DM) this substantially increases the available methane per tonne of material as received (from 97.4 to 166.5 m^3 CH_4 kg^{-1} VS). This makes RCG one of the most productive boreal energy crops in terms of methane yield per hectare when biomass productivity is included (Lehtomäki et al., 2008), although delaying harvest until early fall was found to reduce specific and areal methane yields (Massé et al., 2011). With acid hydrolysis, biogenic hydrogen can also be produced from RCG (Lakaniemi et al., 2011). Because multiple harvesting within a single growing season is also possible (Seppälä et al., 2009), and although yields in the regrowth are lower, the effect is to increase net energy yields by c. 45% (Kandel et al., 2013b). Other conversion routes for RCG include supercritical fluid extraction (Aysu, 2012) and hydrothermal liquefaction (Biller et al., 2016).

Although RCG has high productivity and produces good quality hay (Wrobel et al., 2009), its use as a fodder crop is limited to certain low alkaloid cultivars (Jakubowski et al., 2011) (see Section 5.2.2).

5.5 Phytoremediation

The remediation potential of RCG is an emerging area of research, with reported applications in phytoextraction, phytodegradation, as a bioindicator for pollutants, and use in wetlands or engineered passive treatment systems. RCG also has considerable potential in the physical phytostabilization of soils or sediments.

5.5.1 Phytoextraction of Inorganic Contaminants

One of the earliest suggested uses of RCG for phytoextraction was to address diffuse areas of radioactive pollution: higher levels of ^{90}Sr were found in RCG growing downstream of known sources of nuclear contamination (Rickard and Price, 1990), while laboratory studies showed the potential to remove radioactive ^{137}Cs from contaminated soils, such as in the area around Chernobyl (Lasat et al., 1997). In this study, higher shoot concentrations, bioaccumulation factors, productivities, and net extraction rates were found for cabbages. However, this comparison overlooked the ease of cultivation, harvesting, perennial growth, and overall cost effectiveness of using RCG. The use of high productivity but lower translocation potential energy crops is a recognized alternative to the conventional approach of phytoextraction using hyperaccumulators (Dickinson et al., 2009). However, in field-scale trials on the same five brownfield sites the concentrations of Zn, Cu, Cd, and Ni were higher in short rotation coppice willow (Tora or Torhild commercial hybrid clones) than in either *Miscanthus* × *giganteus* or RCG, although the latter did show better establishment, tolerance, biomass yield, and persistence (Lord, 2015). Nevertheless, increases in Zn, Pb, and Co in RCG growing in contaminated sediments or urban soils confirm its use as a bioindicator and potential for phytostabilization of metal-polluted sediments (Polechońska and Klink, 2014b). RCG is also an accumulator of N, P, Ca, Mg, and K compared to water or bottom sediments, so it could be used to remove nutrients from eutrophic lakes or rivers (Polechońska and Klink, 2014a). Uptake of dissolved Zn from urban drainage produces isotopic fractionation (i.e., a lower δ 66Zn‰), so RCG can be used to trace metal translocation, first from the roots to the leaves, then to the stem to be deposited. Thus lower concentrations of heavy metals are found in the aboveground plant parts, although these may still represent a greater removed mass due to their greater biomass (Vymazal, 2016). When used in constructed wetlands, RCG can help achieve significant reductions in biological oxygen demand, suspended solids, and ammonium by nitrification (Surampalli et al., 2000). RCG biomass was also found to be a suitable low-cost organic substrate for treatment of acid mine water discharges (Lakaniemi et al., 2010).

5.5.2 Phytodegradation of Organic Contaminants

Laboratory studies have also demonstrated that RCG growth reduced the concentration of polychlorinated biphenyls (Aroclor 1248) and 2,6-dinitro-*o*-cresol (2-methyl-3,5-dinitrophenol) in soils, and trinitrotoluene in low-organic matter soils, but was ineffective on the polyaromatic hydrocarbon pyrene (Dzantor and Woolston, 2001; Chekol et al., 2002, 2004). RCG was also found to have a strong potential to neutralize toxic compounds (Urbanek et al., 2005). However, compared to switchgrass, RCG appeared less tolerant to chlorophenols such as 3,4-dichloroaniline (Brazier-Hicks et al., 2007). Phytodegradation of the xenobiotic explosive RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine) has been shown in RCG, by photochemical degradation within its leaves, known as phytophotolysis (Just and Schnoor, 2003).

5.5.3 Phytostabilization and Phytomanagement

The rapid growth, relatively low contaminant uptake, and dense rooting habit of RCG make it a useful species for stabilization of waste materials or polluted soils to reduce erosion or dispersal (Fig. 5.2A). The root system reaches to more than 3 m and the vigorous rhizomes and roots can fortify the surface of wet soils (Lewandowski et al., 2003). RCG can also tolerate extensive flooding and poor soil aeration (Wrobel et al., 2009), and has been known to survive inundation to water depths of 2.7 m by developing floating rafts. RCG was second only to switchgrass in persistence and biomass yield 10 years after planting on Appalachian mine spoil amended with biosolids (Evanylo et al., 2005), and reduced leaching of ammonium and metals when planted in sulfidic mine tailings amended with sewage sludge and wood ash (Neuschütz and Greger, 2009). In river environments, RCG can rapidly achieve sediment stabilization resistant to 100-year flood events (Bankhead et al., 2017) and increase channel roughness, leading to increased sedimentation and delayed flood runoff (Martinez and Mcdowell, 2016) (Fig. 5.2B). Depending on the context, the rapid establishment and persistence of RCG can be viewed either as beneficial or detrimental to other environmental objectives, contributing

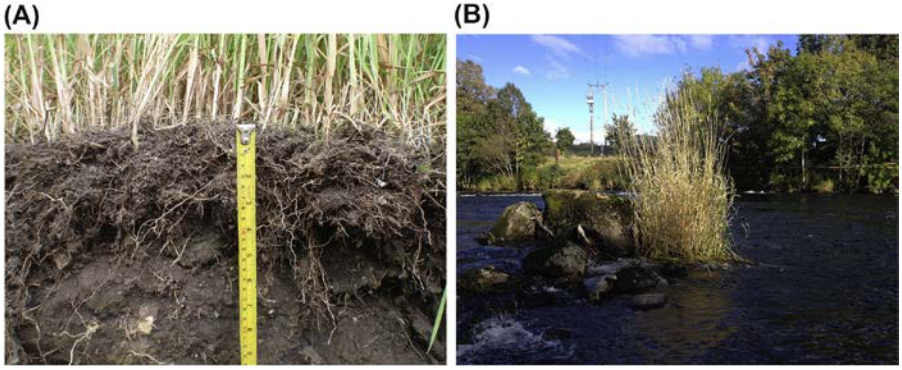

Figure 5.2 Characteristics illustrating the potential of reed canary grass for environmental applications. (A) Root development on a clay-capped brownfield site. (B) Midstream establishment in river gravel in an upland watershed.

to the reputation of nonnative European genotypes of RCG as an invasive species in wetlands of the United States (Lavergne and Molofsky, 2004; Jakubowski et al., 2011).

5.5.4 Greenhouse Gas Mitigation and Carbon Sequestration

Bioenergy cropping systems can help mitigate greenhouse gas (GHG) emissions and it has been shown that RCG can provide a net sink for GHGs even when soil carbon (C) is assumed to reach equilibrium and C sequestration in soil is not counted (Adler et al., 2007). GHG mitigation through fossil fuel replacement represents a significant part of the GHG budget of energy crops, although the level of GHG mitigation is a function of the C intensity of the fossil fuel being replaced (Cannell, 2003). In addition to the savings accrued from fossil fuel substitution, energy crops can also help mitigate GHGs through lower cultivation emissions and from carbon sequestration. For example, Shurpali et al. (2008) demonstrated that respiratory carbon losses from RCG crops were lower than both afforested and cultivated organic soils. Additionally, Hyvönen et al. (2009) showed that RCG could be grown on organic soils, such as peat extraction sites, without high N_2O emissions, and it has also been shown that cultivation on abandoned peat extraction sites results in a decrease of the GHG flux of these areas, which are then converted from net sources to net sinks of C (Mander et al., 2012). The cultivation of bioenergy crops can result in soil C sequestration, although Don et al. (2012) suggested that land use change for bioenergy should be restricted to land that is or has been cultivated, as any conversion of native vegetation or perennial grasslands can cause C losses from soils, which compromises GHG savings. Xiong and Kätterer (2010) showed that RCG exhibits a high capacity for C accumulation in belowground organs and that this attribute, together with root turnover, suggests a high C input to soil that may result in positive soil C balances. Kandel et al. (2013a) measured GHG fluxes from several RCG systems established on drained fen peatlands and found that all of the systems were net sources of GHG but suggested that these emissions could be offset through fossil fuel replacement. However, Ní Choncubhair et al. (2017) found that early establishment and rapid canopy growth in RCG facilitated a net C sink in the first 2 years of growth (-319 and $-397\,\mathrm{g\,C\,m^{-2}}$, respectively) and that peak seasonal C uptake occurred in May.

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Bamboo Production for Industrial Utilization

6

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6.1 Introduction

Bamboo refers to a large group of fast-growing woody grasses that can be sustainably cultivated in frequent and short-cycled harvesting schemes in many parts of the world. Bamboo stands can be managed by individual producers and its production does not require large investment. This makes bamboo an ideal crop for rural development, especially in developing countries. Sustainable bamboo production and utilization are considered to be directly relevant to many of the UN sustainable development goals (SDGs) that are targeting important aspects of poverty reduction, housing and urban development, as well as use of renewable energy, combating climate change, and land degradation (INBAR, 2015a,b).

Bamboo is a versatile and widely utilized plant, with many traditional applications including edible shoots, toothpicks, chopsticks, crafted baskets and mats, tools, musical instruments and artwork, horticultural crop support sticks, fuel, erosion control and soil protection, housing construction material, and fuel. For the modern food and biobased industries, specific bamboo properties are very favorable for a wide range of applications, such as paper and pulp, cellulose in dietary fiber food additives or textiles, biochemicals, and bioenergy. Bamboo is cultivated as an ornamental crop or with the purpose of erosion control protection and carbon sequestration; the uses of bamboo are many fold (Section 6.2). The young shoots of selected species are harvested as a vegetable crop in many Asian countries and bamboo extracts are used in medicines and beverages. The mature culms are of light weight and very strong and therefore frequently used as round poles for scaffolding, building and construction, and as support in horticulture and tree nurseries. Straight bamboo culms can be easily split lengthwise, yielding long strips that can be used for chopsticks production or weaving of handicrafts, mats, and baskets, or are glued and compressed together into strong laminates and strong composite beams. Different technologies have been developed for extraction of the fibers from the culms for production of paper and pulp or textiles. Bamboo also is used for the production of energy, e.g., charcoal.

Bamboo industries in China and many other countries show a continuous growth with voluminous production projections for the coming years. In contrast to most commodity crops there are very limited statistics available for production and trade in bamboos. For countries other than China the production data are most often unreliable. This can be ascribed to the fact that local markets for bamboo and bamboo

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Table 6.1 International harmonized system codes (HS codes) of bamboo products

Commodity	HS code	Product
Vegetable plaiting materials	14 01 10	Bamboos
Vegetable food preparations	20 05 91	Bamboo shoots
Wood and articles of wood	44 02 10	Bamboo charcoal
	44 09 21	Bamboo flooring
	44 12 10	Plywood, veneer, and laminated bamboo
Manufactures of plaiting materials	46 01 21	Bamboo mats/matting/screens
	46 01 92	Bamboo plaits
	46 02 11	Bamboo basketwork
Pulp of wood or of other materials	47 06 30	Bamboo pulp
Paper and paper products	48 23 61	Bamboo paper articles
Furnishings	94 01 51	Seats of bamboo and rattan
	94 03 81	Furniture of bamboo and rattan

products are still informal and do not enter economic statistics (Hoogendoorn, 2017). Since 2007, world trade statistics for bamboo and bamboo products have been published by INBAR and included in the UN Comtrade database.[1] Much of the bamboo trade remains in the informal sector and internal markets, and will not be visible in these international export and import data. The total volume of bamboo exports (including wood products, furniture, and vegetables) has been ranging between 120 and 150 kT yr^{-1}, while for bamboo pulp this remains below 100 kT yr^{-1}. Exported bamboo is widely used in horticulture as growth support. Bamboo charcoal exports amount to 30–75 kT yr^{-1}. The growth potential for bamboo commodity products is considered large. In Table 6.1 the currently traded bamboo products are listed with their HS custom codes. Apart from bamboo products traded from China and India, Colombia has also shown that there is good market potential for bamboo culms as building material. When combined with basic processing such as preservation, producers may earn $12 per culm on the housing market. With 1000 culms available per hectare per year, and considering a worldwide housing deficit among millions of the urban poor, bamboo could become a major income source for rural communities. And here too lower-quality bamboo as well as residues can be used as feedstock in other biobased industries.

Large-scale use of bamboo for economic production of the wide range of industrial products may have its limitations because harvesting is difficult to mechanize and variable stem maturity may affect the consistency of harvested crop quality. Another drawback is that plantations have to be established vegetatively, making it

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[1] https://comtrade.un.org/data/.

labor intensive, slow, and relatively costly on a large scale. The dedicated production of energy from bamboo crops by thermal conversion or second-generation fuels may be less profitable than nonenergy uses as these will have a more attractive market value. However, the market volume of solid fuel is high and might offer possibilities to bamboo-producing countries other than China.

Bamboo production residues and discarded bamboo products, however, would be most suitable for charcoal production, for example. The fuel quality of bamboos for thermal conversion is lower than for most woods but is generally better than for herbaceous biomass.

The concept of whole crop biorefinery, i.e., separation of the biomass into its constituents, is most appropriate for bamboo and enables optimal use of bamboos in a variety of products, from high-end uses down to combustion of residues for the generation of heat and electricity. That this concept works can be observed already in China's Linan county (Zhejiang), where bamboo has been developed into a sustainable feedstock for the biobased economy of this region (Kant and Chiu, 2000). It should be noted that the use of chemical agents (such as boron salts and resins) to impregnate and glue the bamboo for use in building materials limits other uses such as most energy applications.

Also in other regions of the world bamboos are considered to be a key resource for development, such as in South America (Colombia) and Africa (Ethiopia, Kenya, Uganda, and Ghana) (Friedrich, 2017). In countries with a tradition in bamboo architecture, the unique properties of bamboos are recognized. For example, *Guadua* (*Guadua angustifolia*) is promoted by the Colombian authorities who have established a national bamboo building code that is of particular importance for earthquake prone areas. Other areas in the world with great bamboo potential include East Africa (Ethiopia, Kenya, and Uganda) with over a million hectares of Ethiopian lowland bamboo (*Oxytenanthera abyssinica*). This species grows on dry land and poor soils and holds great promise as feedstock for many uses, including building materials, flooring, edible shoots, and pulp and paper. In Ghana, promising experiments on arid lands for bamboo production have shown a potential for local employment development (Goedknegt and Meester, 2017).

To realize the full potential of bamboo as sustainable CO_2 neutral feedstock for the biobased economy, more research and development is required focusing especially on propagation, stand management, and ecologically sustainable biorefinery processing methods, but also on the economic use of the produced biomass. It is hoped that this publication leads to improved understanding of the potential of bamboo in the biobased economy.

6.1.1 General Characteristics

Bamboos belong to the family of grasses (Poaceae), just like important food crops such as rice, wheat, other cereals, and sugar cane. Especially, woody bamboos are known for their high versatility, with numerous traditional, modern, and potential uses.

Bamboo is the common name for a group of rapidly growing tall woody grasses, taxonomically classified as Bambusoideae with around 1400 species worldwide, divided into more than 100 genera, uniting three tribes of geographically divided species (Table 6.3), e.g., Bambuseae (68 genera): woody tropical bamboos; Arundinarieae (30 genera): temperate woody bamboos; and Olyreae (21 genera): herbaceous bamboos mainly from the tropical Americas (Clark et al., 2015). Distinction is made between "running" (monopodial) bamboos and "clumping" (sympodial) bamboos, with the latter dominating tropical regions that are typically growing closely together in clumps (Fig. 6.1). Typical features of the bamboo plants are distinct protrusions on the culm, called "nodes," with intermediate parts called "internodes."

6.1.2 Growth and Distribution

Some species of bamboo can reach over 30 m in height in only a few months or may grow faster than 1 m day^{-1}. Bamboo is also a very tough and hardy plant, surviving under the harshest of conditions of drought and frost. Bamboo plants are perennial; once established, there is no need for replanting, as harvested culms are replaced by new shoots emerging from the underground rhizome system (as illustrated in Fig. 6.1). This property enables sustainable, regular harvesting of culms and thus stable income for producers, with only low investments, but restricts mechanization of harvesting.

Bamboo has a wide geographical distribution and is naturally occurring in a range between 40° southern and northern latitudes on all continents, except Europe (Fig. 6.2). Although bamboos occur in both tropical and temperate climates, warm and humid conditions are preferred by most species. An annual mean temperature of 20–30°C is preferred with precipitation levels of 1000–2000 mm. Some species, such as *Dendrocalamus strictus*, survive under drier conditions in India, with 750–1000 mm of annual precipitation. Most bamboos are found to prosper on sandy loam to loamy clay soils.

Figure 6.1 Sympodial (running) and Monopodial (clumping) bamboos. (http://www.buzzle.com/articles/types-of-bamboo.html).

6.1.3 Natural Bamboo Forests and Plantations

Assessments of the total area of bamboo worldwide varied from 22 (ICBR, 2004) to 31.5 million hectares for the year 2010 (FAO, 2010), which amounted to just over 3% of the forest area in these regions. Bamboo occurs as patches within forests or as clusters outside; areas are therefore difficult to assess (FAO, 2010). There also seems to be a lack of consistency in the assessment of bamboo total area between countries over the years. Most bamboo is harvested from natural stands, though plantations of bamboo are expanding, particularly in China. Over the last few decades bamboo areas have expanded. Since 1990 the area of bamboo has increased by an estimated 1.6 million hectares worldwide (FAO, 2010), mainly in China.

In Table 6.2 the most recent estimates of bamboo areas are given for regions and some important countries.

The most productive bamboo species may yield over 30 t ha^{-1} dry matter lignocellulosic biomass each year. On average the yield of the most common bamboo crop in well-managed forests or plantations in China can be up to 25 t ha^{-1} yr^{-1}.

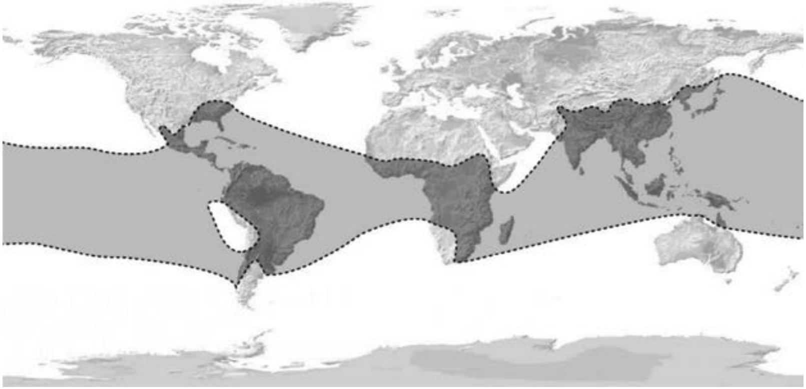


Figure 6.2 Worldwide distribution of bamboo species (INBAR).

Table 6.2 Bamboo areas in regions of the world based on FAO (2010)

Region/country	Area of bamboo (1000 ha)
Total Africa	3,627
China	5,712
India	5,476
Total Asia	17,360
Total Europe	0
Total North and Central America	39
Brazil	9,300
Total South America	10,339
Total world	31,470

Most bamboo in the world grows in natural forests, with China being the exception. China has currently an estimated 4.5 million hectares of bamboo plantations (*Phyllostachys pubescens*), of which 60% is concentrated in four contiguous provinces: Fujian, Jianxi, Hunan, and Zhejiang. An additional area includes "mixed and mountain natural bamboo stands." The yields of bamboo plantations vary considerably depending on species, management, and location. Management is different for optimal production of fresh bamboo shoots or culms for timber or a combined harvest. Very productive species may yield more than 30 $\mathrm{t\,ha^{-1}\,yr^{-1}}$ dry matter of culms. A well-managed bamboo plantation yields on average 25 $\mathrm{t\,ha^{-1}\,yr^{-1}}$. Tsinglee canes and tonkin sticks (*Pseudosasa amabilis*) that are frequently used in horticultural nurseries are produced mainly in Guangdong province.

Other nations, in both tropical and temperate regions, are lesser known for their, often considerable, bamboo reserves. The internal market and trade of bamboo and bamboo products are still mostly informal and do not enter economic or trade statistics (Hoogendoorn, 2017). For example, Peru's Alto Purus region has approximately 2.5 million hectares of tropical rainforest dominated by bamboo species. And Chile has around 3.5 million hectares of temperate forests (Valdivia) with the presence of indigenous *Chusquea* bamboo species. These bamboos are rarely used as an economic crop but are important for the local ecosystems (Reid et al., 2004).

Africa too has large areas of natural bamboo stands. Ethiopia can boast the largest bamboo coverage in Africa, with over 1 million hectares of Savannah bamboo (*O. abyssinica*). The African highland bamboo, known as *Yushania alpina*, occurs between 2000 and 3500 m above sea level.

Flowering of many bamboo species occurs irregularly each year in a cycle of 3–7 years of so-called mast flowering. Some species may flower at irregular intervals or only once in 40 years or longer. This may occur in synchronized massive flowering and fruiting followed by dying of the plants (Keeley and Bond, 1999). Other species do not die after flowering but may occasionally flower thereafter.

6.2 Current Uses and Status as Fibrous Biomass Crop

6.2.1 Bamboo Traditional Utilization

Numerous commercial uses of bamboos are known, which can be broadly categorized as:

- Horticultural support sticks;
- Plaiting;
- Tools and utensils (including chopsticks and toothpicks);
- Scaffolding;
- Construction and composite materials (flooring, plywood, veneer, and laminated bamboo);
- Furniture, furnishings;
- Pulp, paper, and boards;
- Textiles and tissues;
- Handicrafts, musical instruments, and gift items;
- Food and feed products (shoots, dietary fiber, tea leaves, and beverages);
- Energy (combustion) and charcoal.

Bamboo species are very different from each other and for that reason their uses and processing technologies are often species specific.

6.2.2 Bamboo Species: Growth and Development

The most typical characteristic feature of bamboos is the division of the hollow stems or culms into nodes and internodes. This is a property they have in common with other grasses that belong to the same large botanical family of Poaceae (=Graminea), which is the largest family of monocotyledonous plants. Other typical common features are the leaves that are composed of a blade, with a sheath and ligule (Fig. 6.1).

The two types of bamboo rhizomes that are distinguished are the monopodial ("runners") and sympodial ("clumpers") bamboos. The temperate zone bamboos (*Phyllostachys* and *Pleioblastus*) are often runners and can be invasive, while the tropical species grow close together in clumps (*Bambusa*).

The possibility for growth in the intercalary meristem—e.g., in between the nodes—is an adaptation of grasses that allows recovery after grazing and fire damage. The intercalary growth allows bamboos to grow rapidly. Bamboo grows in height between the internodes from base to tip. The young culm is still rather soft and becomes harder with increasing stem height. The culm maturing and strengthening process proceeds through lignification and deposition of cellulose in the fiber cell walls. The thickness of the stem is increasing only slightly during development, but the diameter does not increase after the culm is fully grown. Unlike many other tropical grasses, bamboos do not show the highly efficient C_4 photosynthetic pathway for CO_2 fixation (Renvoize, 1985).

Bamboo is known to accumulate silica in its tissues (Collin et al., 2012), especially in the leaves of sympodial bamboos, and can reach up to $100\,\mathrm{mg\,g^{-1}}$ SiO_2. In the stems, between 5 and $10\,\mathrm{mg\,g^{-1}}$ SiO_2 is present, which may have consequences for the pulping process conditions. In the hollow internodes of old culms, sometimes a white siliceous rich deposition is found, known as tabashir, that is used in Chinese and Indian traditional medicine.

6.2.3 Fiber Morphology

The bamboo stems contain thick-walled fiber strands associated with the vascular bundles embedded in the parenchyma tissues (Parameswaran and Liese, 1976; Youssefian and Rahbar, 2015) that provide the mechanical strength of the culms. The bundles that become visible as the small darker dots when the stem is cut transversely are composed of spindle-shaped fiber cells of c. 2 mm length and 15 μm width. In microscopic view these regular-shaped groups of fiber cells are distributed evenly with regular distances in between. At the edges the bundles are closer together than in the interior parts of the culm, near the soft pith and hollow center (lacuna). The fiber cell walls have a characteristic concentric multilayered structure of alternating broad and narrow lamellae with different cellulose fibril orientation (Ray et al., 2004). Each layer shows fibrils with almost longitudinal orientation (2–5 degrees from the cell axis) in the broader outer lamellae, while the narrow lamellae are nearly horizontally or

Table 6.3 Important bamboo species, properties, and uses

Bambusoideae	Species	Common name	Diameter (cm)	Height (m)	Country/ production
Olyreae	Herbaceous				
Arundinarieae	Temperate woody				
	Yushania alpina (=*Arundinaria alpina*)		8–10	10–20	East Africa
	Abies amabilis (=*Pseudosasa amabilis*)	Tonkin cane			China
	Aucuba japonica		4–5	2–5	
	Phyllostachys pubescens	Moso bamboo	10–30	10–35	China
	Passiflora edulis		10–15	18–20	China
	Phyllostachys bambusoides		12–20	15–25	China
	Phyllostachys makinoi				
	Phyllostachys aurea		5	7–9	China
	Phyllostachys nigra		2–3	5–7	
	Pleioblastus viridistriatus	Dwarf green-stripe		0.6–1.2	
	Chimonobambusa spp.				
Bambuseae	Neotropical woody				
Guaduinae	*Guadua angustifolia*	Guadua	10–15	10–30	Mexico–Argentina, Colombia, Ecuador
Chusqueinae	*Chusquea culeou*	Culeo			South America
Bambuseae	Paleotropical woody				
Bambusinea	*Bambusa vulgaris*		5–10	8–20	
	Bambusa bambos		8–9	28	South Asia
	Bambusa arundinacea		15–18	26–30	South Asia
	Bambusa atra		2–4	5–8	Indonesia
	Bambusa cacharensis		5–6	11	
	Bambusa balcoa		6–8	14–15	India
	Bambusa blumeana				Indonesia
	Bambusa polymorpha				Myanmar
	Bambusa textilis	Weaver's bamboo			South China
	Bambusa tulda				India, Thailand

Uses					
Construction	**Laminates**	**Pulp**	**Crafts**	**Shoots**	**Other**
+			+ weaving furniture		Horticulture
					Fishing rods horticulture
+	+	+		++	
				++	
			Furniture	+	Ornamental
					Ornamental
+	+	+	+ Furniture		
+		+	+ Furniture		
+		+	+	+	Medicine Limited use
+					Handicrafts, baskets, thatching
+		+	Furniture		Limited use
+			Furniture, baskets		
,			Weaving	+	
		+	+ Furniture		

Table 6.3 Important bamboo species, properties, and uses—cont'd

Bambusoideae	Species	Common name	Diameter (cm)	Height (m)	Country/ production
	Bambusa heterostachya				Malaysia Indonesia
	Bambusa nutans				Northern India, Bangladesh, Thailand
	Bambusa emeiensis (*Neosinocalamus affinis*)		5	8	China
	Bambusa oldhamii				China, Japan, Thailand
Bambusinea	*Oxytenanthera abyssinica*		5–15	5–15	East Africa, Ethiopia
Bambusinea	*Dendrocalamus strictus*	Iron bamboo	5–12	8–18	India, Nepal, Myanmar, Thailand
	Dendrocalamus giganteus		30–35	30–35	Myanmar, Northern Thailand
	Dendrocalamus asper	Petung			Northern India, Nepal, Thailand, Laos, Myanmar, Vietnam
	Dendrocalamus farinosus				China
	Dendrocalamus merrillianus				Thailand
	Dendrocalamus latiflorus				China, Myanmar
Bambusinea	*Thyrsostachys siamensis*		3–6	7–13	Thailand, Laos, Vietnam
	Thyrsostachys oliveri		5–8	12–25	
Bambusinea	*Gigantochloa apus*		5–12	12–20	Myanmar, Thailand, Indonesia, Malaysia
	Gigantochloa levis				Philippines, Indonesia, Malaysia, China, Vietnam
	Gigantochloa pseudoarundinacea				Indonesia
Bambuseae	*Indosasa sinica*			8–10	China
Melocanninae	*Melocanna baccifera*	Muli			Bangladesh, India, Myanmar
	Melocanna bambusoides		5–15	13–23	
Melocanninae	*Cephalostachyum pergracile*				Northern India Thailand, Yunnan, China
Melocanninae	*Ochlandra* spp.		2–5	2–6	Southern India, Sri Lanka

Uses					
Construction	**Laminates**	**Pulp**	**Crafts**	**Shoots**	**Other**
					Poles
+		+	Furniture		
					++
+			+ Weaving	+	
+		+	Tools	(+)	
+		+		+	
+		+	+ Furniture, tools	++	Musical instruments, chopsticks
				+	
		+	+ Furniture	+	Thatching
+			+ Furniture	+	Fences
+			Furniture, baskets	(Bitter shoots)	
+			Furniture	+	Fencing
+			+ Furniture	+	Pipes, chopsticks, toothpicks
+		+	Matting	+	Roofing, thatching
			+ Baskets		
		+	+ Matting		

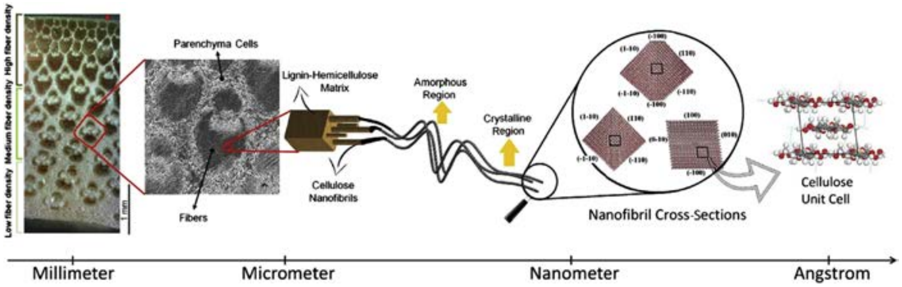


Figure 6.3 Bamboo fiber structure.
Youssefian, S., Rahbar, N., 2015. Molecular origin of strength and stiffness in bamboo fibrils. Scientific Reports 5, 11116.

transversely oriented (c. 85 degrees). High lignin contents are observed between fiber cells in the middle lamellae and especially in the cell corners, while in the cell wall the narrow lamellae contain relatively higher lignin concentrations.

6.2.4 Bamboo Composition

The majority of practical uses of bamboos are linked to the properties of the stiff and lightweight hollow woody stems of the plants. The cross-section of bamboo stems shows evenly distributed fibers and parenchyma cells with thick secondary walls (Fig. 6.3). The density of the bamboo structure is different with the age of the stem (Wang et al., 2012a,b). Older stems are known to be stronger and stiffer. The development of bamboo culms is known to proceed very rapidly, much as the result of elongation of the internodes. The composition of young and older bamboos shows significant differences with respect to cell wall constituents cellulose hemicellulose and lignin.

Cell wall composition varies between nodes and internodes (Liese and Weiner, 1996). The bamboo internodes have on average a typical composition of 40%–45% cellulose, 25% lignin, and 25%–30% hemicellulose or pentosan (Fengel and Shao, 1984). The cellulose deposition in the secondary fiber cell walls occurs after elongation of the internode is complete. In general the percentage of hemicellulose is relatively higher in young stems and in the bottom parts of the culm. See Table 6.4 for an overview of the biochemical composition of selected bamboo species.

6.2.4.1 Cellulose

Detailed analysis of the crystalline morphology of the cellulose in natural bamboo fibers shows typically allomorph type I_β as the dominant phase, while similar crystallinity is measured when compared to other fiber crops (cotton, flax, and ramie) with relatively large crystallite sizes (He et al., 2007). At the nanoscale the bamboo fiber cell wall structure was studied with atomic force microscopy (Zou et al., 2009), which revealed cellulose nanograin structures as the basic building blocks of the cell walls, and with nanoindentation the ductility of the bamboo cell wall was demonstrated.

Table 6.4 **Biochemical composition of bamboo species (Daza et al., 2013)**

Species		***Guadua angustifolia***		***Bambusa vulgaris* var. *vulgaris***	***Dendrocalamus strictus***	***Guadua amplexifolia* Presley**
Maturity stage		Young	Mature	Mature	Mature	Mature
Extractives	Water	7.74	5.63	15.03	9.26	15.35
	Ethanol	2.96	1.25	1.42	1.19	2.26
	Total	12.23	10.21	18.02	11.97	21.21
Polysaccharides	Arabinan	0.66	0.60	0.69	0.67	0.59
	Xylan	16.38	13.95	16.62	15.34	13.47
	Galactan	0.23	0.14	0.16	0.14	0.24
	Glucan	41.29	40.21	36.04	36.60	32.16
Lignin	AIL - ash	20.27	23.72	21.22	24.80	19.17
	ASL	0.90	1.00	0.87	0.82	1.09
Ash	Ash	4.04	5.25	2.91	5.69	4.43

AIL, acid-insoluble lignin; *ASL*, acid-soluble lignin.

6.2.4.2 Hemicellulose

The hemicellulose in bamboo consists mainly of arabinoxylans with different ratios (0.3–1.7) of Ara:Xyl (Peng et al., 2012a,b). The pentosan structure is typical for grasses with a backbone of →4)-β-D-Xyl*p*-(1→ residues that is frequently substituted at 2-*O* and/or 3-*O* with side chains of one or more α-L-Ara*f* units or acetyl groups (6%–7%) and the presence of some (1→2)-linked 4-*O*-Me-α-D-glucuronic acid side groups (Peng et al., 2012a,b). In the early development stage, high branching of arabinoxylans is observed, while in the lignification stages most branching disappears. The attachment of diferuloyl ester groups at the side chains is reported to cross-link the polysaccharides to the lignin complex in the cell wall when cell elongation is completed (Ishii, 1997). Part of the xylose extracted from bamboo cell walls is derived from xyloglucan, which is ubiquitously present in plant primary cell walls.

Besides the dominant pentosan fraction the occurrence of significant amounts of β-glucan with β 1→3- and 1→4-linked glucose monomers was demonstrated to be present in extracts of young shoots (Edashige and Ishii, 1998). This β-glucan is reported to be deposited in secondary walls of phloem cells in the active growing stages of the internodes.

Practical uses for hemicellulose fractions from bamboo were reviewed (Peng and She, 2014) and are restricted to potential use as biomaterials (hydrogels, films, and stabilizers) and starting material for the preparation of chemical derivatives (Section 6.4). The biorefinery and conversion of hemicellulose fractions by fermentative processes to ethanol or other substitute chemicals have been studied. Different depolymerization processes catalyzed by acid or enzymes to produce oligosaccharides or monomeric sugars have been described. Xylitol production from bamboo xylans as a low calorific sweetener in food industries has received much attention.

6.2.4.3 Lignin

The lignin deposition occurs early in the epidermis and increases with age in the cell walls of mature fibers and parenchyma (Lybeer and Koch, 2005). This process proceeds from bottom to top and from the outside inward, especially in the first growing season (Itoh, 1990). Around the xylem vessels, lignification is most strong (Suzuki and Itoh, 2001). Lignin is a polyphenolic polymer that is found in the cell walls of all land plants and is associated with the strength of woody structures. Typically for the Poaceae the lignin of bamboo is composed of guaiacyl, syringyl, and hydroxyphenylpropan units and has uniquely attached *p*-coumaric acid ester groups (Higuchi, 1987).

The lignin content of bamboo culms (20%–25%) is at the high end of the normal range of 11%–27% reported for nonwoody biomass and is found to be closer to the ranges for softwoods (24%–37%) and hardwoods (17%–30%) (Li et al., 2010). This would suggest that bamboo should have similar physical properties and uses as conventional softwoods and hardwoods. Its high lignin content contributes to the relatively high heating value of bamboo, and its structural rigidity makes it a valuable building material (Scurlock et al., 2000).

Similarly, the glucan content of 32%–42% is comparable to the reported cellulose content of softwoods (40%–52%) and hardwoods (38%–56%). The cellulose content in this range makes some bamboo species a useful feedstock for paper production and processes that convert cellulose to fuels and chemicals (Scurlock et al., 2000).

6.3 Primary Production Methods for Bamboo

6.3.1 Selective Harvesting

Clear-cutting or mowing of bamboo is rarely recommended, except maybe for some smaller species, or for salvaging stands that face biomass deterioration as a result of (mast) flowering. Clear-cutting is thought to decrease the vitality of bamboo stands and recuperation of the stand takes a considerable amount of time.

Selective harvesting or pruning is a far more sustainable method of maintenance, resembling uneven-aged forest management of timber species. Bamboo culms appear as shoots from the rhizome system with their final diameter already reached, whereas their maximum height may be reached in less than a year. Depending on the species and its use, the culm commonly needs several years to attain its harvestable quality, usually up to 5 years. Given its heterogeneity, with culms in all age classes, bamboo stands are suitable for short-cycle harvesting systems. In this way, bamboo stands can supply steady revenue streams for local producers and also ecological benefits are guaranteed through permanent bamboo coverage. A disadvantage, however, may be the impossibility of reduced harvesting costs through mechanization (Van Dam et al., 2013). This is especially important when bamboo is considered for energy production purposes, for example, for combustion or for large-scale ethanol production.

The national bamboo harvesting standard in Colombia prescribes that only mature culms are to be cut to a maximum of 25% of the bamboo stand each year. With an optimal stand density of around 4000 culms per hectare, each year 1000 culms can be sustainably harvested on every hectare. This equals approximately 40 m^3 or 26 tons dry matter per hectare per year. These figures, however, vary greatly among species, growth site, and seasons. The pictures in Fig. 6.4 show an example of different stages of bamboo development (*Guadua* bamboo).

Figure 6.4 Bamboo growth stages.
Photo credit: R. Poppens

6.3.2 Harvesting and Postharvest Treatment

Bamboo culms are usually cut with a knife or machete (Fig. 6.5). At least for hollow bamboos, it is imperative that a clean cut is made, with no chance for water to collect in the cavities of the remaining stump. This could result in rotting of the rhizome system and subsequent deterioration of the bamboo stand. Also organic matter and dead culms should be removed to allow space for new shoots to develop.

There is a correlation between stand density and culm diameter size. The denser the bamboo stand, the smaller are the diameters produced. Which diameter is best depends on the application.

Freshly harvested bamboo material is rich in sugars and starch and is subject to early decay by insects or fungi, especially under tropical conditions. Therefore water storage or smoking is performed to remove fermentable carbohydrates (Liese, 2005). Depending on end-use applications, safe and economic preservation methods may be applied, such as with boron salts. At all times, transport distances and storage time should be kept minimal.

6.3.3 Bamboo Propagation and Establishment

There are two common propagation methods for bamboo: seed propagation and vegetative propagation, from separated rhizomes or cuttings also called cloning. Running and clumping bamboo types require different propagation. Rhizomes with buds and culms with two nodes can be taken from the parent plant of running bamboos for

Figure 6.5 Transportation of freshly harvested bamboo.
Photo credit: R. Poppens

replanting. For a clumping bamboo a selection of a piece of rhizome that has strong shoots, roots, and buds can be cut and replanted.

6.3.4 Seed Propagation

From bamboo seed (Fig. 6.6), seedlings can be produced and easily multiplied in nurseries before planting in the field. Although suitable for large-scale propagation, seed propagation has serious limitations. Many bamboos flower infrequently or gregariously, often at very long intervals, or produce seeds with low survivability. Seed propagation is feasible for Moso bamboo, but for *Guadua* bamboo and Savannah bamboo, producers must rely on cloning.

6.3.5 Vegetative Propagation (Cloning)

One advantage of cloning is that the propagation material can be selected from mother plants of known characteristics (Fig. 6.7). This is not necessarily the case with seed

Figure 6.6 Flowering bamboo and seeds.
Photo credit: R. Poppens

Culm cutting Developed clump Transplanting Nursery beds

Figure 6.7 Planting steps.
Photo credit: R. Poppens

propagation. The disadvantage of cloning is that it is labor intensive and therefore expensive. The cloning techniques for tropical bamboos are via rhizome cuttings and branch and culm cuttings. The new plantlets are grown from healthy buds on sections of rhizome, culm, or branches. Temperate running bamboos are cloned by clump division. Alternative methods include in vitro propagation, where large quantities of bamboo material could be produced in a short period of time. However, this requires large investments and achieved plantlet qualities are often insufficient.

For *Guadua* bamboo, a more efficient method is available: propagation with *chusquines*. These are small plantlets that naturally appear from the underground rhizome after the *Guadua* clump has been harvested or damaged. The chusquines are collected and reproduced in a nursery bed. After 2–3 months, stems have multiplied and can be separated and transplanted into planting beds or pots. This process can be repeated until plants are obtained with sufficient size and diameter for planting in the field. Though commonly used for *Guadua* bamboo, this method may not be suitable for other bamboos. It may take 7 years before mature *Guadua* culms are obtained of sufficient quality.

6.4 Bamboo Processing for the Different Markets

Among the fiber crops, bamboo is categorized as a nonwood fiber class of stalk fibers, e.g., derived from mostly monocots such as straws of cereals, grasses, reeds, rattan, and bamboo, in contrast to bast fibers (jute, hemp, flax, kenaf, ramie) and seed hair fibers (cotton, kapok), which are dicots.

Different processing sequences are used to produce a range of products from the bamboo culm (Scheme 6.1) ranging from textiles to green chemicals and fuel. The processes will be described in the following sections.

6.4.1 Bamboo Textile Manufacturing

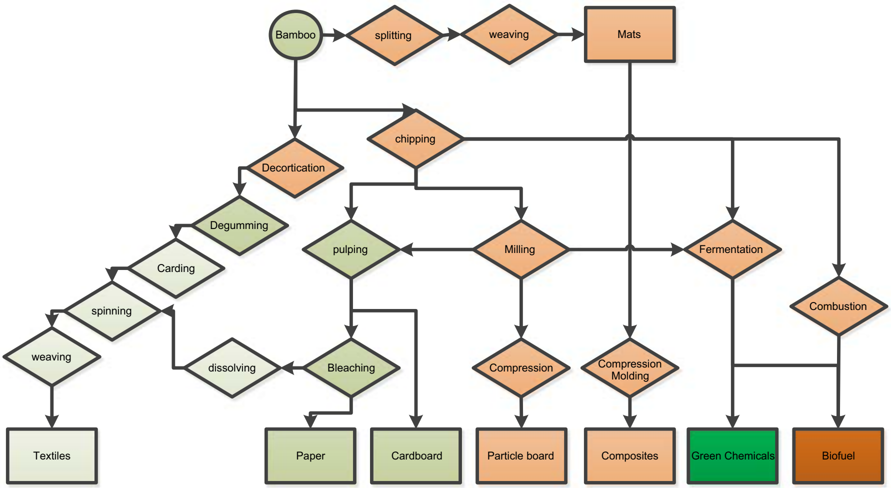
Textile production from bamboo is a rather recent innovation. Manufacturing of commercially attractive textile fabrics from bamboo can be attained by different processing routes. Because of the relatively short fiber cells of bamboo the fission process of bamboo into small and even fiber bundles such as in bast fiber crops (flax, hemp) is difficult to achieve. However, in China some bamboos have been shown suitable for bamboo linen production (e.g., *Bambusa textilis*). The use of retting procedures and enzymes in the degumming process provides tools for controlled fiber bundle production.

The most important are:

- 100% bamboo long fibers (Scheme 6.2);
- Regenerated bamboo cellulose or viscose/rayon (Scheme 6.3).

6.4.1.1 Thermomechanical Fiber Processing

One way is to extract the fiber bundles as they are present in the bamboo culms by mechanical and chemical processing steps. The bamboo culms are processed according



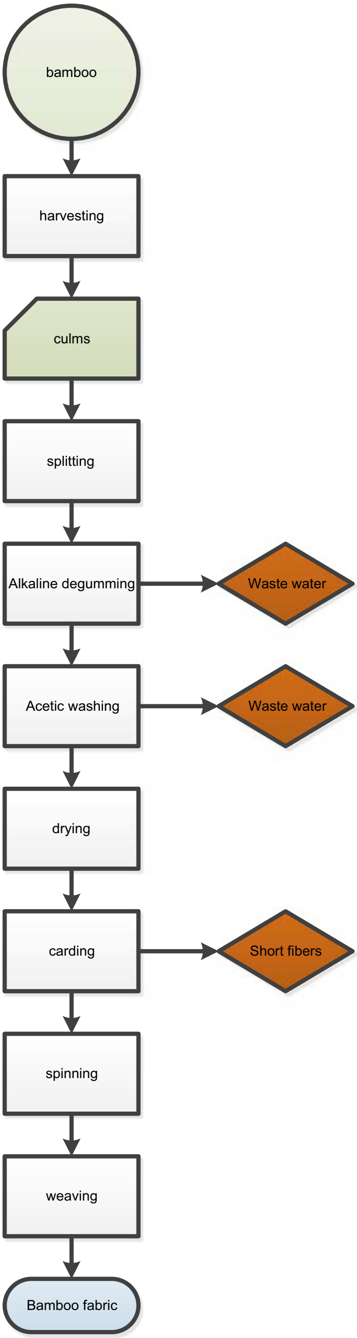
Scheme 6.1 Simplified scheme of bamboo biorefinery processing.

to Scheme 6.2. First, the culms are split lengthwise followed by an alkaline cooking and degumming step. Fiber bundles are composed of many cells that are oriented in parallel strands of 70–90 mm that are linked together through the lignin-rich middle lamellar cements. The fiber cells in the bundle are on average 2 mm in length and have a diameter of 10 µm with no or very small lumen. A typical fiber bundle has a diameter of 200–300 µm. The bundle length can be limited to the internode length or run all along the culm. At the nodes the bundle may be deformed. For practical mechanical spinning and carding processing the fiber length may be reduced. The textile yarn fineness of bamboo fiber bundles is c. 2.6 dtex[2] (range 1.3–5.5 dtex), which is in the range of a fine jute fiber yarn (Yueping et al., 2010) but coarser than cotton or linen yarns. These fibers are suitable for spinning of yarns and the production of strong but rather coarse fabrics (Scheme 6.2).

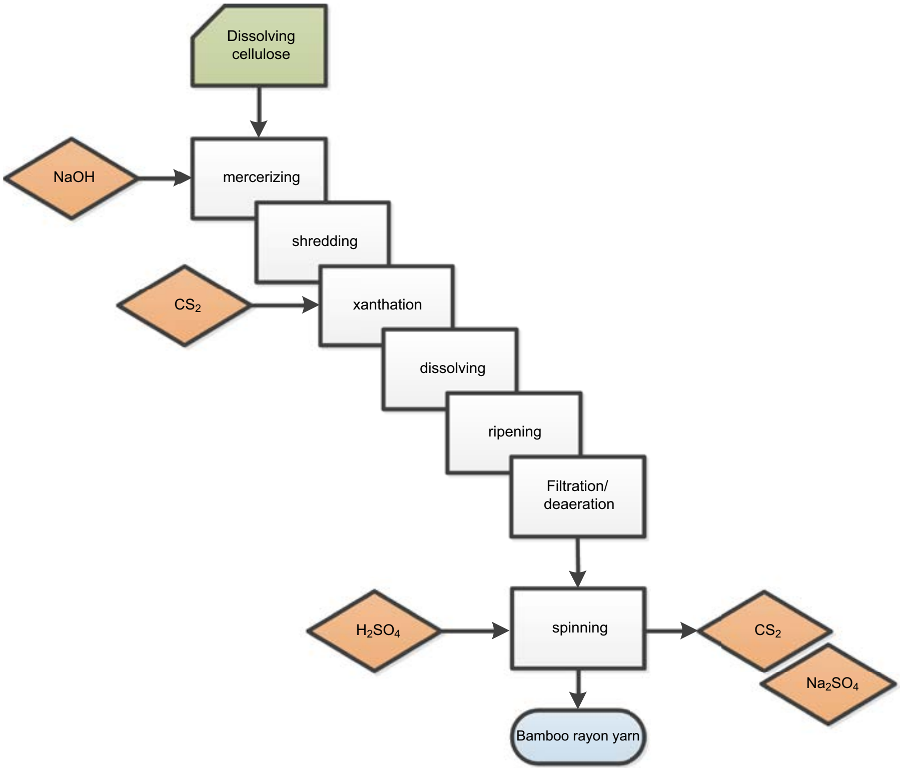
6.4.1.2 Regenerated Fiber Processing

For the production of regenerated bamboo fiber the extraction of all noncellulose constituents from the culm is required. Commonly, a pulping process is used, such as for paper production, e.g., Kraft pulping. The pulped fibers need to be further bleached to high purity-dissolving cellulose pulp and then they can enter the viscose process. Strict control of ash content of the pulp is an important requirement. Prehydrolysis processing of bamboo fiber by cooking at an elevated temperature (170°C, 1 h) results in partial removal of organic acid and pentosan by autohydrolysis while loosening the fiber structure and making penetration of the cooking chemicals easier (Ma et al., 2011). Different cooking chemicals can be applied. Most common are the Kraft and

[2] dtex, Mass of yarn per 10,000 m.



Scheme 6.2 Bamboo long fiber textile process.



Scheme 6.3 Bamboo viscose-regenerated fiber process.

sulfite pulping processes. Alternatively, alkaline (sodium/anthraquinone) or organosolv (ethanol, or acetic or formic acid) cooking procedures can be used followed by appropriate bleaching sequences to reach the α-cellulose purity (>95%) and brightness of dissolving pulp.

The most common method of industrial production of bamboo textiles involves the production of regenerated cellulose from purified bamboo pulps (Scheme 6.3). Like wood-based pulp, bamboo pulp can be further purified into dissolving cellulose, which is used as feedstock for the production of cellulose textiles and cellulose derivatives. Regenerated cellulose (viscose rayon) is by far the largest of the cellulose-derived biopolymers (c. 3.5 million tons worldwide), followed by cellulose esters (>1 million tons), and cellulose ethers (<1 million tons). More than 60% of chemical-grade pulp is used to produce regenerated cellulose, mostly from wood cellulose. Regenerated cellulose is used to produce both fibers and films. The textile fibers are economically much more important than films.

Bamboo viscose fiber is marketed in China as a very versatile textile raw material that competes with synthetic textile yarns and natural fibers such as cotton, wool, linen, and silk. Exceptional qualities have been claimed for bamboo fabrics. The fineness of bamboo viscose will be in the range of 80–160 dtex for filament yarns.

In apparel, it offers a high wearing comfort by being soft, cool, and highly moisture absorbent. Bamboo fiber fabrics have a silk-like feel and appearance. The fabrics are advertised as being extremely cool and moisture absorbing due to the microstructure in the fiber, and combined with antiultraviolet properties it is especially suitable for comfortable and safe clothing in warm climates. The antibacterial and bacteriostatic properties of bamboo textiles are ascribed to a biologically active nonallergenic component called "bamboo kun" that is reported to be present in the bamboo stems. This substance, which is believed to protect bamboo plants from diseases and pests, is (re) combined with the bamboo cellulose for obtaining these antimicrobial properties.

6.4.2 Pulp and Paper Production

Bamboo is used as a nonwood pulp source for the production of paper and board. Bamboo fibers are of interest as reinforcing pulp fiber since the fiber length (2 mm) comes close to the range of softwood fibers and its good mechanical strength properties are favorable. The selected pulping process for bamboo delignification is often Kraft pulping, which is favored over alkaline pulping (Vu et al., 2004). Kraft pulping uses cooking at elevated temperatures (150–170°C) of the chipped wood in alkaline sulfate followed by a bleaching step. One of the most frequently reported issues of bamboo pulping is the presence of silica that accumulates in the black liquor and its consequences for the chemical recovery process. The presence of silica in the bamboo is a major technical obstacle for efficient chemical recovery of the pulping liquor. The silica contents of bamboos increase with maturity, while the overall ash content of mature bamboo is lower than in younger samples.

Only about 7% of the world's virgin cellulose pulp is made from nonwood sources (mainly straw, bagasse, and bamboo). In the European Union, the United States, and Canada paper industries practically only wood pulp is currently used. Globally dwindling forests and shortage of wood supply are the drivers for the search for sustainable alternatives. In 1998 China produced c. 17 million tons of nonwood pulp (Food and Agriculture Organization statistics), which was 84% of the total pulp production, including c. 1 million tons of bamboo pulp. Due to environmental concerns, many of the small bamboo and rice straw pulp mills have now been closed. Most bamboo pulp is used in the internal Chinese market. Currently less than 100 kT yr^{-1} is exported worldwide.

The special high water retention characteristic of bamboo fiber when compared to wood fiber paper making is correlated to the multilamellar structure and the internal fibrillation due to the beating process, resulting in rapid decrease of freeness and increase of water-retention values (Wai et al., 1985). This property is much appreciated in the application of bamboo microcellulose in the food industry.

Different pulp grades can be made from bamboo pulp that find various markets for value addition. Lower grades milled or refined fibers can be converted to building boards (cement bonded or glued particle board) or fiber-reinforced polymer composites. Kraft pulping yields pulp for liner board and paper bags. Bleached fibers can be used in pulp blends for printing- and writing-grade papers. In the production of Kraft paper, 20%–25% of the pulp mix can be replaced by bamboo pulp, as was reported by one of Colombia's principal pulp and paper plants. Highly purified bamboo cellulose fibers may be converted to dissolving pulp (Batalha et al., 2011) and bamboo textile fibers (Scheme 6.3). New fiber lines with adapted chemical pulping have been installed in China in the last decade for the production of bamboo pulp that finds value-added use in the production of bamboo textiles.

6.4.3 Bamboo Biorefinery and Production of "Green" Chemicals

In biorefinery and pulping processes the focus is on the production of valuable components in the (lignocellulosic) biomass that are extracted for economic utilization. The residues preferably are disposed of or at the most burned for generation of process heat. However, these fractions contain various components with interesting properties. So far the enhanced use of extractives from the process for cellulose production has been investigated for different related resources such as sugar cane bagasse, *Miscanthus*, or sarkanda grass. The black liquor from bamboo pulping or digested fermentation feedstock from biorefineries has potential use as a feedstock for "green chemicals" and resin production.

Bamboo noncellulosic polysaccharides or hemicellulose is mostly composed of xylan. Xylan is a C5 sugar (pentosan) that has been studied for conversion into many food and nonfood applications, sweeteners (xylitol), or liquid fuel solvents or chemicals. For example, furfural is produced in an acid-catalyzed process from pentosan and may be converted into furan resins by hydrogenation and controlled polymerization of the furfury alcohol (Mamman et al., 2008). New catalysts for the hydrogenation process are patented. From the C6 sugar fraction, levulinic acid can be derived simultaneously (Gürbüz et al., 2012).

Another approach for the production of "green" chemicals from biomass is the hydrothermal cracking processes (Fisher–Tropf), similar to petrochemical industries (Buragohain et al., 2010). Commonly, for this type of conversion, large-scale operations are required.

6.4.4 Fiber Composites and Engineered Bamboo Products

6.4.4.1 Bamboo Veneers and Boards

Bamboo finds increasing application in wood substitute products such as fiber boards (MDF, HDF), particle boards and laminated lumber, veneers, and ply-bamboo (Oriented Strand Board). The strong bamboo fibers can be applied as splits (2 m), filaments, macrofibers (0.25 mm), microfibers (pulp, 20 μm), or nanofibers (20 nm) by applying different mechanical and chemical processing steps (da Costa Correia et al., 2015). The culms are therefore split and planed to remove outer skin and inner soft tissues or are cut and refined into smaller particles, chips, or flakes. The bamboo fibers are then hot pressed with resins to form a board or laminate structure. The current industrial bamboo fiber composites and engineered structural materials are manufactured by utilizing synthetic thermoset resins (e.g., phenol formaldehyde/urea formaldehyde/epoxy/methylene diphenyl isocyanate) to glue the particles or fiber bundles (Yu et al., 2014; Sharma et al., 2015a). The properties are dependent on the morphology and orientation of the fibers used (Osorio et al., 2011).

Studies were performed (Saito et al., 2013) to manufacture binderless boards by hot compression of bamboo powder, utilizing the self-bonding properties of intrinsic components (e.g., lignin, hemicellulose, and extractives). Steam explosion was also used as a pretreatment of bamboo for manufacturing binderless boards with satisfactory properties for indoor uses (Luo et al., 2014).

6.4.4.2 Plastic Composites

Other types of composite materials are produced, similar to wood polymer composites, with bamboo fiber filled or reinforcement thermoplastic composites with matrix polymers such as polypropylene, polyethylene, and polyesters, including polylactic acid. Much research has been done on the manufacturing of cellulose fiber-reinforced plastic composites as (interior) car parts. Up to 60% bamboo fibers or particles can be mixed in the molten plastic matrix to form the desired shaped compounds by extrusion or injection molding. Combined with polypropylene, bamboo fiber was demonstrated to have excellent material properties. Synthetic or biobased plastics may utilize bamboo cellulose fiber as reinforcement (length 2.5 mm, diameter 12.4 μm). For the production of fully biobased materials, developments in the area of biocomposites are reported with bamboo reinforcement of renewable polyesters (polylactic acid, polyhydroxyalkanoates), polyamides, or biobased polyethylene. Surface modifications and alkaline extractions have been used to enhance the composite mechanical properties and compatibility of the fibers with the polymers (Manalo et al., 2015). Thermal treatment is used in the laminated composite production to increase resistance to decomposition in exterior applications (Sharma et al., 2015b). In the different processes of cellulose extraction the intrinsic original glue (lignin, hemicellulose) is chemically removed. These polyphenols (lignin) and pentosans (xylan) can be converted to renewable glues and green chemicals. The production of furan resins from hemicellulose (now largely produced commercially from sugar cane bagasse) has been demonstrated to yield high-quality resins for production of thermoset composites.

Production of rod-shaped nanocellulose crystals from bleached bamboo was successfully demonstrated, with length distributions depending on the hydrolysis conditions applied (Brito et al., 2012). Despite the high expectations, demonstration of viable processes for nanofiber composite production based on bamboo has not yet emerged.

6.4.4.3 Mineral Composites

Bamboo as construction material combined with mineral binders has been the subject of study for the substitution of steel reinforcement in concrete slabs and columns (Ghavami, 2005). Bamboo fiber may find use in lightweight construction materials, especially in earthquake-resistant construction (Terai and Minami, 2011). The weak bonds between the cement and bamboo can partly be overcome by the selection of pretreatment of bamboo fibers and mineral mortar composition (Agarwal et al., 2014). The performance of bamboo cement composites and the durability of bamboo fibers are not significantly affected by the harsh alkaline conditions of the cementitious matrix (Lima et al., 2008).

6.4.5 Food Additives (Microcellulose)

Bamboo fiber is widely used in food industries and is much appreciated as an ingredient because of its water-binding and texturizing properties in many processed food products varying from bakery products, dairy products, meat and fish products, beverages, sauces, and dressings (Li et al., 2008). Bamboo fibers have a high ranking position as a stabilizer in functional foods (Hse et al., 2007). Its function as a low-calorific additive is used to avoid moisture loss and to preserve taste and flavor of food products. Food products using bamboo stabilizer may be labeled as all-natural products (Dunnewijk, 2017).

6.4.6 Food and Health Products

The use of young bamboo shoots as a vegetable is very popular in the Asian kitchen, but is quite unknown and uncommon outside Asia. The tasty and nutritional juvenile shoots are receiving attention as popular healthcare food products. The shoots of many bamboo species are edible but the genera most commonly appreciated and consumed are *Bambusa*, *Dendracalamus*, and *Phylostachys*. Locally, varieties of *Gigantochloa*, *Thyrsostachys*, *Sinocalamus*, *Melocanna*, *Guadua*, *Schizostachyum*, and *Teinostachyum* are also consumed (Chongtham et al., 2011).

In addition, the crispy taste of bamboos is much appreciated. The health aspects of bamboos are summarized as: rich in nutrients, protein, carbohydrate, minerals, and vitamins and low in fats. The amino acid composition of the proteins is rich essential amino acids, e.g., serine, methionine, isoleucine, leucine, phenylalanine, lysine, and histidine (Qiu, 1992) and therefore a valuable addition for human nutrition. The neutraceutical effects are ascribed to the presence of phytosterols and high content of dietary fibers.

Bamboo shoots are prepared for human consumption in different ways. Fresh shoots will quickly deteriorate because of the high moisture content and lose their quality as an acrid taste is released (Nirmala and Sharma, 2008). The shoots of some species can be consumed raw, but many require detoxification as they may contain cyanides (taxiphyllin) and must be boiled, fermented, or canned. For commercial purposes canning is the most used method for preservation. In many traditional dishes, fermented bamboo shoots are used in pickles and curries, while wines, beers, and liquors are also produced (Satya et al., 2010). Bamboo shoots have been analyzed for their composition. The cell wall structures of young shoots are not yet lignified.

The many health claims for bamboo-derived products originate from traditional Chinese and Indian medicinal recipes. Scientific evidence for such claims is provided by modern research as antioxidant, antiinflammatory, antifungal, antimicrobial effects or cholesterol-lowering properties of bamboo extracts. The many bioactive components that are found in bamboo species are phytochemicals that belong to categories such as terpenes (carotenoids, phytosterols), phenols (lignans, flavonoids), saponins, etc.

Tabashir is a silica-rich solidified particle found inside some bamboo species and is formed by reaction to injuries caused by wasps. It is considered to have stimulant, astringent, febrifuge, tonic, cooling, antispasmodic, and aphrodisiac properties (Dharmananda, 2004).

6.5 Energy and Fuels

The use of bamboo for bioenergy production processes is much less reported. Bamboo, like any biomass, can be converted to heat and power, to liquid, solid, or gaseous fuels, and to other chemical products through a variety of conversion processes. The available processing routes range from conventional uses of biomass such as firing for cooking and heating, to modern production processes such as converting sugars into (second-generation) ethanol, to combusting and cocombusting biomass with coal for heat and power production, to further advanced technologies such as gasification and transport fuel production (Montaño et al., 2012). Here we will review the most relevant properties of bamboo as a bioenergy feedstock and recent studies addressing the main issues in dedicated bioenergy production from bamboo.

6.5.1 Biomass Properties

Bamboo presents common characteristics with many other biomass feedstocks regarding heating value and chemical composition. The properties of bamboo differ according to the species, plant section, maturity stage, season, cultivation practices (e.g., fertilizers application), and production site. Table 6.5 lists average properties of bamboo and other typical biomass feedstocks reported in the literature (Scurlock et al., 2000; Kwong et al., 2007; Vassilev et al., 2010; Chen et al., 2011). Bamboo's overall composition and heating value lie between clean wood and herbaceous material. Culms of woody bamboos, which are mature or dry, would make the most suitable combustion fuel. By then, the bamboo culm has reached its maximum weight, and its moisture and starch levels have lowered. Dry culms have lost their strength, therefore requiring less power for cutting and chipping as compared to younger culms.

Bamboo also presents advantages over other lignocellulosic feedstocks such as higher crop productivities and higher biomass densities—both relevant characteristics that can result in reduced production and transport costs. Furthermore, the production of bamboo does not require the use of seeds and plastics for baling, and requires no or only small amounts of fertilizer. These present key advantages in the economic and environmental performance of biomass value chains.

6.5.2 Thermal Conversion of Bamboo

A limited number of evaluations of bamboo utilization for large-scale combustion have been made (Scurlock et al., 2000). More recently, the potential of bamboo to

Table 6.5 **Properties of bamboo versus typical biomass feedstocks**

Feedstock		Bamboo culm	Cane bagasse[a]	Wheat straw[a]	Wood
Higher heating value (dry)	$MJ\,kg^{-1}$	17–20	18–20	16–19	17–20
Bulk density	$kg\,m^{-3}$	**300–700**	150–200	160–300	200–500
Crop yield	$ton\,ha^{-1}\,yr$	**10–40**	7–15	3–12	5–20
		Overall composition (dwt%)			
Cellulose		40	35	38	50
Hemicellulose		20	25	36	23
Lignin		20	20	16	22
Others[b]		2–10	20	10	5

[a] Data from Brown, R.C., Brown, T.R., 2013. Biorenewable Resources: Engineering New Products from Agriculture. John Wiley & Sons.

[b] Includes proteins, oils, and ashes.

Modified from Daza, C., Zwart, R., Camargo, J.C., Chávez-Díaz, R., Londoño, X., Fryda, L., Janssen, A., Pels, J., Kalivodova, J., Amézquita, M.A., Arango, A.M., 2013. Torrefied bamboo for the import of sustainable biomass from Colombia. (Informe Final del Proyecto de Investigación). In: Second Generation Torrefied Pellets for Sustainable Biomass Export from Colombia Pereira, Colombia, Universidad Tecnológica de Pereira, Centro de Energía de Holanda, Imperial College UK.

substitute coal for sustainable electricity production was analyzed (Montaño et al., 2012; Daza et al., 2013).[3] The study included the technical, economic, and sustainability assessment of the import of torrefied bamboo pellets from Colombia to the Port of Rotterdam. As part of the technical assessment, properties of several bamboo species were analyzed and the results are presented in Table 6.6.

The proximate analysis and heating value of the bamboo species are comparable to wood. However, the ash content of bamboo is higher than that of wood and roughly lies in between clean wood and herbaceous material. The ash composition of a solid fuel determines its suitability for thermal conversion; properties such as low ash melting temperature can have a detrimental effect on the process. The major inherent ash-forming elements in biomass include Si, Al, Ca, Mg, Na, Fe, K, S, and P. Especially K/Na and Cl cause operational problems. The high K content of bamboo reacts with other ash-forming elements (i.e., Si, Cl, S, and P) leading to slagging, fouling, and corrosion-related problems, as well as agglomeration in fluidized-bed systems (Montaño et al., 2012). Strategies to improve the fuel quality and combustion behavior of bamboo are:

- Use of additives;
- Removal of soluble salts and minerals with techniques such as washing and hydrothermal treatment.

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[3] The study by Daza Montaño et al. was carried out in the framework of the Netherlands Programme Sustainable Biomass Import.

Table 6.6 **Proximate and ultimate analyses of bamboo culm samples and reference biomass feedstocks (Daza et al., 2013)**

Bamboo species/other	***Guadua angustifolia***	***Guadua amplexifolia***	***Dendrocalamus strictus***	***Bambusa vulgaris***	***Chusquea subulata***	**Wheat straw**	**Wood willow**
Age (years)	5	NA	NA	NA	NA	NA	NA
Higher heating value (MJ/kg)	18.35	18.78	18.73	19.05	18.56	16.57	19.35
Proximate and ultimate (mass fraction %, dry fuel)							
Volatiles	74	74	75	76	74	71	81
Ash @ 815°C	4.9	3.8	5.6	2.7	6.9	7.8	1.5
C	47.00	47.00	47.00	48.00	46.10	43.82	44.70
H	5.90	6.00	5.90	6.10	5.40	5.28	5.70
N	0.70	0.80	1.20	0.60	0.80	0.42	0.20
O	42.00	43.00	41.00	43.00	42.20	43.31	46.15
S	0.07	0.19	0.16	0.05	0.13	0.11	3.00
Cl	0.11	0.09	0.04	0.02	0.12	0.27	0.01
Ash composition (mg kg^{-1} fuel, dry fuel)							
Si	16,453.0	6,209.0	21,105.0	7,570.0	20,259.6	20,271.0	69.1
Na	6.3	11.8	13.5	5.0	13.5	48.3	127.2
K	10,684.0	16,402.0	3,656.0	6,907.0	7,158.4	15,466.0	1,420.0
Cl	1,086.0	859.0	438.0	213.0	1,205.0	2,682.0	100.0
S	736.0	1,861.0	1,579.0	548.0	1,283.0	1,100.0	30,000.0
As	<1.4	<1.4	<1.4	<1.4	<1.4	1.0	0.7
Cd	<0.1	<0.1	0.1	<0.1	<0.1	0.3	1.9

Cr	1.1	1.1	1.3	1.0	3.0	4.7	2.1
Cu	2.6	3.0	5.4	2.2	9.5	3.7	3.1
Pb	<0.6	<0.6	<0.6	<0.6	2.1	0.0	1.9
Zn	8.0	22.3	32.7	7.5	31.6	28.7	61.8
P	869.0	1,283.0	1,786.0	892.0	2,766.2	1,030.0	651.0
Mg	253.0	290.0	1,617.0	225.0	481.9	642.0	378.0
Al	8.5	13.0	5.0	5.9	20.8	109.9	18.9
Ca	260.0	380.0	346.0	215.0	379.5	2,282.0	3,899.0
Ti	0.5	0.6	0.3	0.5	1.2	1.4	2.1
Mn	2.6	7.4	7.0	4.2	8.9	28.1	12.0
Fe	16.0	20.2	21.7	16.5	53.7	114.6	30.0
Sr	2.1	1.7	1.0	0.6	4.8	8.2	14.4
Ba	2.4	1.2	0.9	0.7	2.9	42.2	1.2

6.5.2.1 Additives

The use of additives is an alternative to reduce the ash-related operational problems in biomass combustion. Additives refer to a group of minerals or chemicals that can change the ash chemistry, decrease concentration of problematic compounds, and raise ash melting temperatures in biomass combustion processes. Utilization of additives has been studied and tested for several decades (Wang et al., 2012a,b). Additives can be Al-silicate based, sulfur based, calcium based, and phosphorus based. Improvement was reported of agglomeration trends of bamboo by using halloysite and kaolin mineral additives (De Fusco et al., 2016).

6.5.2.2 Water Washing

Washing the material is an alternative to reduce the concentration of troublesome elements in biomass. Washing could be done in the field or at a processing plant, either by natural leaching with rainfall or by controlled water washing. Natural leaching of herbaceous material has proven to be effective in the removal of detrimental elements for combustion of herbaceous materials (Tonn et al., 2012). Controlled water washing has been studied by several authors. Removal efficiencies of Cl, K, SiO_2, and ash increase as water temperature rises (Deng et al., 2013). Washing of bamboo in the field (natural or in a pool) could be a simple and efficient manner to remove critical elements (e.g., K and Cl) and could be applied in production areas where rainfall and water resources are abundant. The resulting aqueous stream rich in minerals and organic matter could be used for irrigation purposes or for biogas production via anaerobic digestion.

The feasibility and commercial implementation of either system depend on a combination of several factors that include, e.g., scale and cost of production, agronomic practices, water availability, and field-specific factors.

6.5.2.3 Thermal Pretreatment

The physical and chemical properties of untreated bamboo as an alternative to coal generally do not meet the stringent fuel specifications of most thermal conversion processes, similar to most biomass streams with high ash content. Cofeeding of biomass in pulverized coal-fired power plants and entrained flow gasifiers requires a very small particle size after grinding. Bamboo, like other woody and herbaceous biomass, is tenacious and fibrous, which makes it difficult and expensive to grind. The poor grindability of biomass is one of the limiting factors of large-scale biomass production. Furthermore, its characteristics with regard to handling, storage, degradability, and energy density are not favorable in comparison with coal. To an important extent these problems could be solved by pretreating the biomass to increase energy density, grindability, and storage capability.

6.5.2.4 Torrefaction

Torrefaction is an upgrading technology under development that aims to enhance the fuel quality by addressing issues such as energy density, grindability, and storability.

It is performed at temperatures between 250 and 300°C in the absence of oxygen. From the dry biomass fed into the process, typically 70 wt% is retained as the solid product, which represents 90% of the original energy content. After torrefaction, the material should undergo a densification processes that includes grinding and subsequent pelletization or briquetting, which usually requires the use of binders (e.g., starch). Good pellet quality remains a challenge in the densification process of torrefied materials.

Due to its natural binding properties, lignin plays an important role in the densification process. Pellet quality of a material depends on the ability of its lignin to act as a binder in the presence of moisture during densification (Nanou et al., 2017).

6.5.2.5 Hydrothermal Treatment

Hydrothermal treatment (wet torrefaction) allows for combined torrefaction and washing of the feedstock and removes salts and minerals from biomass, further improving the quality of the product. Preliminary tests to produce pellets suggest that hydrothermally treated bamboo at 200°C could be easily dewatered by pressing yielding pellets of high density (Daza et al., 2013). The mild pretreatment conditions might reduce lignin decomposition, therefore keeping its natural binding properties. When the material is hydrothermally pretreated, it is possible to eliminate two of the main obstacles that prevent bamboo from being cofired: first, the high alkali content, as it removes alkali (K and Na) and Cl, and second, it breaks down its fibrous structure, reducing the required energy for milling (Montaño et al., 2012; Daza et al., 2013). Similar findings on hydrothermal treatment are reported (Yan et al., 2017).

The fuel characterization, pretreatment effects (dry and wet torrefaction), grinding energy, and combustion behavior of samples were reported from a 5-year-old bamboo species of *G. angustifolia* in blends with coal and in comparison with woody and herbaceous biomass fuels (Fryda et al., 2014). With both torrefaction and hydrothermal treatment, the grindability of bamboo is considerably improved (Fig. 6.8).

From the fuel characterization results (Table 6.6) it was concluded that *G. angustifolia* is a potential solid fuel due to its elemental composition and high heating capacity. Furthermore, based on a theoretical evaluation of fouling tendencies, it is suggested that bamboo species such as *Bambusa vulgaris* and *D. strictus* could be more suitable candidates for coal substitution.

Dry torrefaction improved the physical qualities of the fuel, such as grindability and moisture content, while wet torrefaction removed salts and minerals from the biomass. With dry torrefaction, the ash concentration of bamboo increases as a result of the decreasing organic content, while wet torrefaction renders a fuel with low ash content, removing above 90% of K and about 80% of Cl (Table 6.7).

6.5.2.6 Combustion Behavior

Combustion simulation trials show the virgin material has a fouling potential similar to herbaceous biomass; dry torrefaction reduces the fouling behavior and wet torrefaction renders a product of high quality that minimizes the risk of fouling and deposition (Fryda et al., 2014).

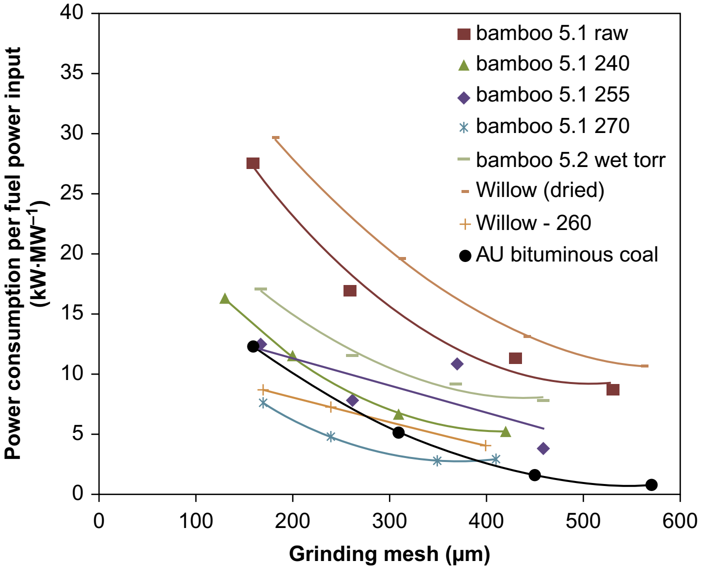

Figure 6.8 Effect of torrefaction temperature and particle size of untreated and torrefied bamboo on grindability (Fryda et al., 2014).

6.5.3 Cooking Fuel and Charcoal

Bamboo can be used as a cooking fuel in several ways: noncarbonized material as a direct substitute for firewood, or after conversion into charcoal as a substitute for wood charcoal. Use as a firewood substitute is an established practice for households in rural Africa. The use of bamboo to produce (industrial) heat, power, or combined heat and power for local usage or for the production of solid biofuel for the export market is being investigated in various African countries (Vis et al., 2013). Bamboo charcoal and briquette production is a simple technology that is used in China (Chen et al., 2014) and promoted in Africa, for example, in Ethiopia, Kenya, and Ghana.

In rural areas, traditional mud ovens are common and are characterized by low efficiencies. Improved technologies for charcoal production technology are mainly based on three typical kiln types: brick, metal, and retort. Each of these kiln types has advantages and disadvantages, and their applicability depends on local conditions, feedstock availability, and financial resources. Pilot projects in African countries mainly use brick kilns and metal kilns (of varied sizes), while the industry retort types are commonly used in the Chinese bamboo processing industry. Charcoal briquettes can be produced at various quality levels (low, regular, premium), depending on the fuel quality, the binder, and the operating pressure.

6.5.4 Pyrolysis

Pyrolysis is the controlled thermal decomposition of biomass occurring at around 500°C in the absence of oxygen, which produces a liquid (bio-oil), a gas (e.g., CO, H_2),

Table 6.7 **Proximate, ultimate, and ash analysis of thermally pretreated bamboo samples**

Fuel	**Raw bamboo *Guadua angustifolia* (5 years)**	**Dry torrefied bamboo *G. angustifolia* (5 years) 255°C**	**Wet torrefied bamboo *G. angustifolia* (5 years)**
Moisture %	12.0	0.3	0.1
Ash @ 850°C	5.1	7.6	4.5
Ash @ 550°C	5.7	7.6	4.9
Volatiles	75	65	76
Higher heating value (MJ kg^{-1})	18.81	20.88	20.28
C	47	51	50
H	5.9	5.5	5.8
N	0.30	0.34	0.27
S	0.084	0.068	0.026
O	43	35	44
Na (±7)	3	3.5	29.4
Mg (±1)	218	169	15.9
Al (±4)	10	9.5	20.61
Si (±90)	12,731	25,906	20,121
P (±15)	482	513	50.7
K (±20)	9,902	9,271	510
Ca (±20)	252	242	396
Ti (±8)	0.5	0.5	0.75
Mn (±6)	2	2	2.1
Fe (±4)	14	11.5	26.14
Zn (±1)	6.3	4	2.7
Pb (±20)	0	0	0.33
Sr (±5)	2.2	2.9	1.2
Ba (±5)	2.5	3.5	1.34
Cl (±20)	1395	949	253
SO_3[a]	0.21	0.17	0.065
Na_2O[a]	0.0004	0.0005	0.0041
K_2O[a]	1.2	1.1	0.061
Cl[a]	0.14	0.095	0.025

[a] S, K, Na, and Cl expressed as SO_3, Na_2O, K_2O, and Cl mass fraction in ash %.

Adapted from Daza, C., Zwart, R., Camargo, J.C., Chávez-Díaz, R., Londoño, X., Fryda, L., Janssen, A., Pels, J., Kalivodova, J., Amézquita, M.A., Arango, A.M., 2013. Torrefied bamboo for the import of sustainable biomass from Colombia. (Informe Final del Proyecto de Investigación). In: Second Generation Torrefied Pellets for Sustainable Biomass Export from Colombia Pereira, Colombia, Universidad Tecnológica de Pereira, Centro de Energía de Holanda, Imperial College UK; Fryda, L., Daza, C., Pels, J., Janssen, A., Zwart, R., 2014. Lab-scale co-firing of virgin and torrefied bamboo species *Guadua angustifolia* Kunth as a fuel substitute in coal fired power plants. Biomass and Bioenergy 65, 28–41.

and a solid (biochar). The resulting products can be valorized as fuels or be further upgraded to higher value products (chemicals, materials). The two main types of processes are fast pyrolysis and slow pyrolysis. These are characterized by different residence times in the pyrolysis reactor and lead to different proportions of the gas, liquid, and solid fractions. While slow pyrolysis favors the production of biochar, fast pyrolysis favors the production of bio-oil (IEA, 2009). In slow pyrolysis, the char, bio-oil, and gas fractions are about 33%, 32%, and 35%, respectively, and in fast pyrolysis they are about 12%, 75%, and 13%, respectively. This technology for thermal conversion of biomass has also been tested for bamboo—mainly focusing on fast pyrolysis—while a few studies have examined slow pyrolysis (Chen et al., 2014).

Bio-oil has been found to be comparable in composition and liquid fuel quality to most other lignocellulosic resources. A bio-oil (weight) yield of 70% was reported from fast pyrolysis of bamboo sawdust in a fluidized-bed reactor operating at 400–500°C and coproducing a low-calorific value gas (9 MJ kg^{-1}) (Jung et al., 2008). The bio-oil could be suitable not only as a fuel but also as a feedstock for the production of high-value chemicals.

Bamboo char has been reported to have a large amount of micropores and a very large surface area, approximately 4–10 times greater than wood char (Kantarelis et al., 2010); therefore bamboo studies have focused on producing activated carbons (Choy et al., 2005; Krzesińska et al., 2006, 2009; Mui et al., 2010). As reported (Kantarelis et al., 2010), the char produced from high-temperature steam pyrolysis of bamboo could be an activated carbon precursor, a solid biofuel, or a reducing agent in metallurgical processes. Powdered activated bamboo charcoal has been shown effective for removal of pollutants such as nitrate, phenols, and heavy metals from waste waters (Mizuta et al., 2004; Wang et al., 2010).

Biochar use for soil improvement has also gained interest over the last few years. Applying biochar to soil is thought to have multiple benefits, from helping mitigate climate change, to managing waste, to conserving soil (Jeffery et al., 2017). Biochar is also widely assumed to boost crop yield. The yield-stimulating effects of biochar may especially benefit agriculture in low-nutrient, acidic soils in the tropics (Jeffery et al., 2017). Therefore biochar application in the soil could be of interest in bamboo-producing regions.

6.5.5 Biogas

Biogas can be produced from the anaerobic digestion of residual streams from bamboo processing. Suitable residual streams are those with high carbohydrate content such as bamboo leaves and the aqueous residual streams from bamboo processing. The latter also tackles environmental issues of the bamboo-processing industry, related to its wastewater rich in organic matter content (Wang et al., 2013). Xia et al. (2016) reported the improvement of the performance of an anaerobic membrane reactor by adding activated carbon from bamboo. Biogas production from lignocellulosic fractions of bamboo residues has also been studied by several authors (e.g., Shen et al., 2014).

6.5.6 Bioethanol

Different bamboo species have been investigated for the production of (second-generation) bioethanol. Various chemical (alkaline and acidic) and enzymatic (e.g., cellulase, xylanase) pretreatments to liberate the sugars for fermentation have been the subject of study. The effect of growth stage on the ease of saccharification and fermentation was demonstrated. As can be expected, young shoots are easier to digest. Steam explosion, ultrasonication, and organosolv pretreatments were studied in many laboratories, mostly in China, Taiwan, and other East Asian countries. An overall sugar yield of 88.6% of original sugar content and an ethanol recovery of $0.467\,\mathrm{g\,g^{-1}}$ sugar were achieved (Yan et al., 2017) based on their proposed integrated scheme of combining ethanol production with the recovery of silica and lignin.

6.6 Bamboo Market Diversification

The world market for commercialized bamboo products has grown fast and, according to some estimations, may be worth US$60 billion (Friedrich, 2017).[4] Despite economic recessions and decline of the trade statistics of bamboo and bamboo products in recent years, it is expected that prospects for bamboo markets are good and expanding (INBAR). Although relied on for thousands of years by rural households, bamboo is quickly becoming a popular feedstock for commercial products such as flooring, furniture, plywood, pulp, paper, building materials, and other products. Currently, 80% of bamboo products are produced in China, particularly in 10 provinces of China's southeast. This region has been showing the way to develop a true "bamboo-based economy" (Jiang, 2017). Bamboo has been developed there as prime feedstock for high-end commercial products for export, whereas residues and inferior qualities are used for lower-value bulk processing. This cascading principle ensures maximum use of available feedstock, with optimal benefits for rural economies, industries, and the environment alike.

6.6.1 Bamboo Biocommodity Development Perspectives, Resources, and Bioeconomic Prospects

Bamboo presents common characteristics with many other lignocellulosic feedstocks and it has the potential to be a sustainable feedstock in the biobased economy, not only for energy purposes but also for the chemicals and materials sectors. Bamboo is commonly perceived as "green" and environmentally friendly. In recent years, significant global markets have emerged for fashionable bamboo textiles and functional food ingredients, as well as for engineered bamboo products. The environmental and socioeconomic impacts of these developments need to be documented. The development of international trade of bamboo commodities requires implementation of

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[4] https://hansfriederich.wordpress.com/2014/09/01/usd-60-billion-the-total-value-of-trade-in-bamboo-and-rattan/.

standardized quality and nomenclature for the products that could be included in the Harmonized System of products codes of UN Comtrade. Detailed life cycle assessments were made for the engineering bamboo products (Van der Lugt and Vogtländer, 2015). Over the full life cycle of optimized industrial production and use, bamboo can have a negative carbon footprint, as credits are gained through carbon sequestration, when at the end of life the products are incinerated to produce electricity. Substitution of currently used fossil-based resins could even enhance the ecological performance.

Significant amounts of bamboo resources are currently not harvested or are unsuitable for manufacturing products. Residues are discarded from processing sites, plantations, and forest management. These can be used for bioenergy or materials production, providing a potential economic use for this material. However, these bamboo resources need to be identified and the feasibility of sustainable exploitation explored. Bamboo is also seen as a material with huge potential for poverty alleviation and livelihood development in producing countries (Hoogendoorn, 2017; Durai, 2017). Therefore technology transfer and market development are needed.

The successful introduction of bamboo in the fuel portfolio of large-scale combustion processes requires addressing issues of feedstock quality, besides the logistics of storage, transport, and supply. The high ash content and critical ash composition rich in Cl and alkali metals requires pretreatments to improve the fuel quality and combustion behavior (washing, hydrothermal, and additives). Further research and development is required for suitable pretreatment techniques and conditions in combination with the formulation of proper additive blends. The advantages of bamboo over other lignocellulosic feedstocks are the high productivities (10–40 ton ha^{-1}yr) and high biomass densities (400–900 kg m^{-3}) (Liese and Tang, 2015a,b). On the other hand, the disadvantages are the selective harvesting that does not allow for clear cutting and easy mechanization. However, manual harvesting creates jobs and income for the rural population.

The estimated cost of the economic and sustainability assessment of the import of torrefied bamboo pellets from Colombia to the Netherlands (Daza et al., 2013) is €5–8 GJ^{-1}, which is within the price range of pellets. The estimated potential greenhouse gas (GHG) emissions reduction, calculated along the complete supply chain, was above 80%. Bamboo is not yet included in the list of the default biomass to bioenergy chains considered in the EU-RED for achieving goals of GHG emission reductions in the power sector. Therefore potential high CO_2 storage needs to be demonstrated and monitoring activities are required.

Industrial diversification means opportunities for increased value of bamboo through cascading effects. For example, in bamboo flooring, only the middle lower sections of Moso bamboo are used. The remainder is sold by farmers to other factories to produce toothpicks, chopsticks, curtains, scaffolding, charcoal, and other products. This has enabled local farmers to increase the value of their bamboo by a factor 2 to 3. Similarly, fiber- and chemical-based industries could be supplied with lower-grade bamboo qualities, such as in the manufacturing of paper, pulp, biobased plastics, and fine chemicals.

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Suitability of Perennial Grasses for Energy and Nonenergy Products

7

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7.1 Introduction

Perennial grasses are herbaceous, lignocellulosic plants. Their chemical composition is made up primarily of structural polysaccharides, namely, celluloses and hemicelluloses, and of lignin (Scordia et al., 2014). In addition, small fractions of nonstructural components, such as extractives, proteins, lipids, pectin, and ash, build up the lignocellulosic biomass (Wyman, 1994). Extractives are a complex mixture of compounds, which can include sugars, terpenoid compounds, and monolignols (Davison et al., 2013).

Structural polysaccharides and lignin constitute the framework of the plant cell wall. The plant cell wall typically consists of three types of layers, namely, the middle lamella, the primary wall, and the secondary wall (Zhao et al., 2012). The latter usually consists of three sublayers, which are termed S1 (outer), S2 (middle), and S3 (inner) lamellae, respectively (Chundawat et al., 2011).

The basic structure of the primary wall is cellulose, a linear chain of several hundred to many thousands of β-1,4-linked D-glucose units, which may coalesce into unbranched microfibrils, which are hydrophobic and highly crystalline (Somerville, 2006).

Hemicelluloses are a class of branched polysaccharides, both pentose and hexose, whose composition and structure vary depending on the plant species. Grasses are composed of glucuronoarabinoxylans, primarily by C5 polysaccharides (xylans and arabinans) and small fractions of C6 polysaccharides (galactans, mannans, and glucans) cross-linking cellulose in the primary wall.

Both hemicellulose and cellulose microfibrils are embedded in the secondary wall by lignin, a complex three-dimensional polyphenolic polymer, whose basic monomeric units are *p*-hydroxyphenyl, guaiacyl, and syringyl phenylpropanoids. As with hemicellulose, lignin varies among species and cell tissue type. Grass species contain all three units in significant amounts with different ratios (Boerjan et al., 2003).

In millions of years of coevolution among terrestrial plants, herbivores, and cell wall-degrading microbes, mechanisms of resistance to both mechanical and biological decay have been developed (Davison et al., 2013); hence, lignocellulosic plants are able to protect their internal sugars and nonstructural components of the plant cell wall from abiotic (e.g., wind, hailstorm, etc.) and biotic (e.g., bacteria, fungi, yeasts, enzymes, etc.) stresses. This structural resistance of the cell wall is known as recalcitrance.

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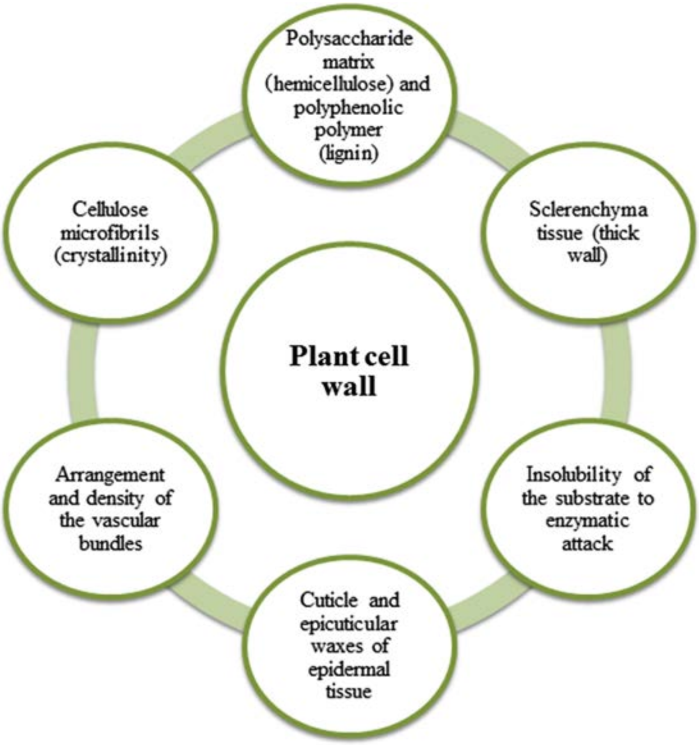

Figure 7.1 Natural factors contributing to the recalcitrance of the lignocellulosic plant cell wall.

According to Himmel et al. (2007), the natural factors contributing to the lignocellulose recalcitrance against chemicals and enzymatic degradation include: (1) cuticle and epicuticular waxes in the epidermal tissue; (2) the arrangement and density of the vascular bundles; (3) the relative amount of sclerenchymatous tissues; (4) the cellulose crystallinity; (5) the degree of lignification; (6) polysaccharides and microfibrils embedded by lignin; and (7) the protection of soluble substrates by hydrophobic and polyphenolic polymers (Fig. 7.1).

Thus the plant cell wall might be considered as a composite material, made of fiber (cellulose), a matrix (lignin, hemicellulose), and fillers (water and nonstructural components) (Monties, 1991). In this analogy, cellulose fulfills the role of steel rods, providing strength over long distances. Hemicellulose represents the wire mesh or cable that wraps around the cellulose rods and lignin acts as the concrete that fills the remaining gaps and sets, holding everything in place while excluding water from the polysaccharide environment (Davison et al., 2013).

One of the most important sustainability characteristics of perennial grasses as biomass crops is thus the lignocellulosic structure of cell walls that contributes to natural resistance to pests and diseases. The lignocellulosic raw material of perennial grasses has been recognized as a low-cost biomass feedstock in contrast to oil crops, sugars, cereals, and other starch-rich crops, fitting well the modern biobased economy concept to promote integrated and diversified biorefineries across Europe. Perennial grass species, such as switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus* spp.), and giant reed (*Arundo donax* L.), have been listed in the latest EU Directive 1513/2015 for the promotion of advanced biofuels, whose energy content shall be considered to be twice that of first-generation crops.

This chapter describes the suitability of lignocellulosic perennial grasses to thermochemical and biochemical process for energy application and other alternative uses toward the biobased economy in Europe.

7.2 Chemical Composition of Perennial Grasses

7.2.1 Main Composition

Perennial grasses investigated in the present study are switchgrass (*P. virgatum* L.), miscanthus (*Miscanthus* spp.), giant reed (*A. donax* L.), reed canary grass (*Phalaris arundinacea* L.), and bamboo (*Phyllostachys* spp.). When perennial grasses are used for energy applications (e.g., heat, electricity, biofuels), biomass chemical composition can be determined for either biochemical or thermochemical conversion pathways. On the other hand, nonenergy applications include nonwood fiber for papermaking, building material, phonic insulating material, mulching and biodegradable products for gardening and animal bedding, or conversion into intermediate as soil organic fertilizer (e.g., biochar, digestate) and green chemistry products (biopharmaceuticals, nutrient supplements, biopolymers, etc.), among others.

Tanger et al. (2013) summarized the main biochemical and thermochemical traits to be determined for bioconversion process optimizations. On the biochemical front, biomass should be characterized in terms of structural and nonstructural carbohydrates, lignin, protein, and extractives; usually, the measurement unit is a percentage of compound in 1 kg of oven-dried material (%w/w).

In thermochemical processes, biomass should be characterized in terms of heating value (MJ kg^{-1}), proximate (volatile matter and fixed carbon) or ultimate analysis (% of C, H, O, N, and S), and ash content (%).

Moisture and elemental ash complete the mass balance of a unit of freshly harvested biomass, and are universal measurements across bioconversion pathways (Tanger et al., 2013). However, biochemical or thermochemical conceptualizations eventually describe the same biomass composition; for example, a higher lignin to cellulose ratio also implies lower H:C and O:C ratios (Couhert et al., 2009).

The main chemical composition for biochemical conversions of selected perennial grasses (as % DM) is shown in Table 7.1. Generally, cellulose (i.e., glucan) accounts for the greatest part, followed by hemicellulose (xylan, arabinan, mannan, and galactan) and lignin. According to Table 7.1, glucan content ranges from 32.0% to 41.0% of the whole biomass. Hemicelluloses account for 21.0%–23.0%; xylan, a C5 polysaccharide, represents the greatest part of hemicellulose content in grasses (i.e., 78% in reed canary grass and 91% in bamboo), followed by another C5, arabinan (4% in bamboo and 12% in reed canary grass). Galactan (a C6 polysaccharide) ranges from

Table 7.1 **Raw material composition for biochemical conversions (% DM w/w)**

Species	Glucan	Xylan	Arabinan	Mannan	Galactan	Lignin
Switchgrass[a]	32.0	17.9	1.9	NA	1.7	21.4
Miscanthus × giganteus[b]	40.1	20.0	1.7	0.1	0.6	22.0
Miscanthus sinensis[c]	41.1	20.1	2.0	0.1	0.7	20.3
Giant reed[d]	34.6	20.4	1.8	0.1	0.7	20.4
Reed canary grass[e]	36.8	16.4	2.6	0.8	1.2	23.1
Bamboo[f]	37.2	19.8	1.0	0.5	0.3	24.3

Data obtained from (a) Xu, J., Cheng, J.J., Sharma-Shivappa, R.R., Burns, J.C., 2010. Lime pretreatment of switchgrass at mild temperatures for ethanol production. Bioresource Technology 101, 2900–2903; (b) Scordia, D., Cosentino, S.L., Jeffries, T.W.W., 2013b. Effectiveness of dilute oxalic acid pretreatment of *Miscanthus* × biomass for ethanol production. Biomass and Bioenergy 59, 540–548; (c) Scordia, D., van den Berg, D., van Sleen, P., Alexopoulou, E., Cosentino, S.L., 2016. Are herbaceous perennial grasses suitable feedstock for thermochemical conversion pathways? Industrial Crops and Products 91, 350–357; (d) Scordia, D., Cosentino, S.L., Lee, J.W., Jeffries, T.W., 2012. Bioconversion of giant reed (*Arundo donax* L.) hemicellulose hydrolysate to ethanol by Scheffersomyces stipitis CBS6054. Biomass and Bioenergy 39, 269–305; (e) Soudham, V.P., Raut, D.G., Anugwom, I., Brandberg, T., Larsson, C., Mikkola, J.P., 2015. Coupled enzymatic hydrolysis and ethanol fermentation: ionic liquid pretreatment for enhanced yields. Biotechnology for Biofuels 8, 135; (f) Li, Z., Jiang, Z., Fei, B., Yu, Y., Cai, Z., 2012. Effective of microwave-KOH pretreatment on enzymatic hydrolysis of bamboo. Journal of Sustainable Bioenergy Systems 2, 104–107.

1% in bamboo to 8% in switchgrass, while mannan content (a C6 polysaccharide) ranges from 0.4% in miscanthus to 4% in reed canary grass. Lignin content ranges from 20% (giant reed and *Miscanthus sinensis*) to 24% (bamboo). Basically, miscanthus species are richer in glucan content (40%–41%); however, giant reed seems to be the species with higher hemicellulose (23%) but, together with *M. sinensis*, with lower lignin content (20%).

The main chemical composition for thermochemical conversion of selected perennial grasses is shown in Table 7.2. The heating value or calorific value is a primary measure of the quality of a biomass and represents the energy available in the feedstock as estimated from the heat released during complete combustion to CO_2, H_2O [gaseous H_2O for lower heating value (LHV), or liquid H_2O for higher heating value (HHV)], and other minor products (Tanger et al., 2013).

The ultimate analysis of a feedstock describes the relative content of individual elements such as C, H, and O, which are also directly related to the structural components of the plant cell wall (e.g., C—O, C—H, and C—C stretching). For instance, structural polysaccharides have a higher C—H and C—O ratio than lignin, while lignin has higher ether bonds and C—C bonds. The calorific value potential of these latter bonds is greater as compared with those of structural polysaccharides (Kim et al., 2012), and, as a consequence, the higher the lignin, the higher the heating value.

Another measurement for thermochemical conversion performance is the proportions of fixed carbon and volatile matter, namely, the proximate analysis (McKendry, 2002). This method separates the biomass into four categories of importance: moisture (water content), volatile matter (gases and vapors), fixed carbon (nonvolatile carbon), and ash (inorganic residue) (Miles et al., 1996; Jenkins et al., 1998; Riley, 2007),

Table 7.2 Raw material composition for thermochemical conversions

Species	Higher heating value ($MJ\,kg^{-1}$)	C	H	O	N	Moisture	Ash
		(% w/w)					
Switchgrass[a]	17.4	43.2	5.7	50.2	0.6	9.7	4.6
Miscanthus × giganteus[b]	16.4*	45.7	5.9	NA	0.08	11.9	2.0
Miscanthus sinensis[b]	16.2*	44.7	6.0	NA	0.09	11.5	3.1
Giant reed[b]	13.3–16.5*	38.5–45.3	5.5–6.0	NA	0.4–1.8	36.6–39.9	5.0–8.0
Reed canary grass[c]	19.5	48.6	6.8	37.3	0.3	14.7	5.5
Bamboo[d]	19.1–19.6	50.9–52.3	5.1–5.4	41.1–42.7	0.4–0.6	8.4–22.6	1.0–4.0

Data obtained from (aMcKendry, P., 2002. Energy production from biomass (part 1): overview of biomass. Bioresource Technology 83, 37–46; Qian, K., Kumar, A., Patil, K., Bellmer, D., Wang, D., Yuan, W., Huhnke, R.L., 2013. Effects of biomass feedstocks and gasification conditions on the physiochemical properties of char. Energies 6, 3972–3986; (b)Scordia, D., van den Berg, D., van Sleen, P., Alexopoulou, E., Cosentino, S.L., 2016. Are herbaceous perennial grasses suitable feedstock for thermochemical conversion pathways? Industrial Crops and Products 91, 350–357 (*lower heating value); (c)Bridgeman, T.G., Jones, J.M., Shield, I., Williams, P.T., 2008. Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties. Fuel 87, 844–856; (d) Scurlock, J.M.O., Dayton, D.C., Hames, B., 2000. Bamboo: an overlooked biomass resource? Biomass and Bioenergy 19, 229–244.

which are related to the relative yields and composition of solid, liquid, and gaseous products generated during pyrolysis and gasification (Tanger et al., 2013).

Total solids (TS), oven-drying biomass sampled at 105°C, and volatile solids (VS), measured as total solids minus the ash content after ignition at 550°C, are preliminary biomass determination to feed anaerobic digestion reactors and to express the substrate digestibility in terms of a normal liter of CH_4 per kilogram of TS or VS added to the test (Angelidaki et al., 2009).

The moisture content of a feedstock expresses the amount of water at harvest and dictates both postharvest practices (e.g., biomass handling and logistics) and bioconversion processes. Relatively dry biomass is more suited to thermochemical conversions, as high moisture (>25%) can cause incomplete combustion, reducing the heating value as the heat liberated during combustion is wasted, evaporating this moisture (Bridgwater et al., 2002). Furthermore, biomass spoilage is fostered at high moisture, with consequent quantity and quality decay.

The ash content and the inorganic elements (i.e., Na, K, Mg, Ca, Cl, S, Si, and the combination of alkali metals with silica) relate to the potential of a feedstock to generate slagging, fouling, and corrosion of the combustion equipment (Monti et al., 2008)—a well-known drawback of perennial grasses as compared with wood species. Also it has been demonstrated that heating values are negatively related to ash content, with every 1% increase in ash concentration decreasing the heating value by $0.2\,\mathrm{MJ\,kg^{-1}}$ (Cassida et al., 2005). Although difficult to generalize, ash content above 5% is a constraint for many thermochemical processes (McKendry, 2002).

Thus preliminary analyses of a feedstock are of paramount importance as a predictor of the biomass quality to maximize bioconversion process efficiencies. Generally, moisture content, calorific value, proportions of fixed carbon and volatiles, ash and inorganic elements, alkali metal content, and cell wall composition should be determined.

While cell wall composition is useful to calculate the theoretical bioethanol production from a dry ton or a unit land area grown with perennial grasses (Scordia et al., 2014), other indices can be useful to predict the performance in high-temperature thermochemical processes (e.g., >600°C), such as ash-melting behavior, alkali index, fouling index, and slagging index.

7.2.2 Factors Affecting Biomass Composition

Perennial grasses for biomass production are largely undomesticated crops (Zegada-Lizarazu et al., 2010) or are still at early stages of development and improvement (Clifton-Brown et al., 2015). Varieties, agronomic practices, and other postharvest logistics are still not optimized to reach their potential in terms of biomass yield and quality in a given environmental condition. In addition to biomass yield, biomass quality is of paramount importance from an engineering point of view. A stable biomass composition delivered at the bioconversion site avoids continual modifications to processing parameters, allowing maximizing bioconversion efficiency without incurring costly and risky operations.

Biomass composition of a single clone of *Miscanthus* × *giganteus* grown at different locations, soil types, weather, nitrogen fertilizations, and dates of harvest under US Midwest conditions showed little, although significant, variation (Arundale et al., 2015).

However, it cannot be ruled out that within a genotype, environmental conditions, plant phenological phases, stand maturity, and field practices influence biomass composition.

In the perennial grass African fodder cane (*Saccharum spontaneum* ssp. *aegyptiacum*), it has been shown that increasing the amount of water for irrigation decreased ash content, bulk density, C, H, and N composition, and LHV; however, moisture content and ash melting point increased. On the other hand, cell wall composition was not affected by water amount (Cosentino et al., 2015).

Allison et al. (2012) reported significant effects on cell wall composition of switchgrass and reed canary grass following increasing nitrogen (N) fertilization. The effect of N application was greater in reed canary grass, which showed small but significant increases in neutral detergent fiber and cellulose content (increases of 3.5% and 7.5%, respectively, compared to unfertilized plots). Both switchgrass and reed canary grass were significantly increased in lignin content under N application (an increase of 10.0% in reed canary grass and 4.4% in switchgrass). However, the authors pointed out that miscanthus responds differently to N fertilizer than switchgrass and reed canary grass, as it reduced cell wall content following increasing N applications (Hodgson et al., 2010).

Scordia et al. (2016) discovered that biomass yield of *M.* × *giganteus*, *M. sinensis*, and three different giant reed clones negatively correlated with C, H, LHV, and glucan content, while positively correlated with N, moisture, total ash, and bulk density. Agronomic management, such as N fertilization, while increasing biomass yield, as reported, for example, with *M.* × *giganteus* and giant reed (Cosentino et al., 2007, 2014), might lead to an increase in ash and consequently a decrease in LHV; nonetheless, it increases the ash-melting behavior and raises the slagging index (Scordia et al., 2016).

Harvest time influences cell wall composition and ash content. In the north of Italy, moisture content of switchgrass dropped from 57% to 37% from fall to winter harvests. In the south of Italy, moisture content changed in overwintering biomass of giant reed and miscanthus: giant reed maintained stable moisture content (~54%), while miscanthus strongly reduced its moisture during wintertime, from 52% to 13%. Winter harvest also implied higher hemicellulose and cellulose contents, while plant cell wall soluble compounds and ash decreased. Lignin content was not affected by harvest time in both miscanthus and giant reed (Monti et al., 2015).

Phenological phase and stand maturity also affect biomass composition. Rhizomatous perennial grasses show a natural characteristic to mobilize and store nutrients to rhizomes during the cold season, to then remobilize them to the aboveground compartments during subsequent spring regrowth (Beale and Long, 1997; Christian et al., 2006; Himken et al., 1997; Strullu et al., 2011). Thus too early harvesting implies a feedstock with higher ash and mineral content, negatively affecting thermochemical conversion processes. In this regard, Jensen et al. (2016) showed how postwinter harvests improve quality criteria for thermal conversion and crop sustainability through remobilization of nutrients to the underground rhizome in a temperate oceanic environment (Wales, United Kingdom). The authors examined 16 miscanthus genotypes (including the commercial hybrid *M.×giganteus*, *M. sinensis*, and *Miscanthus sacchariflorus*), showing different flowering and senescence times, for variation in N, P, K, moisture, ash, Cl, and Si contents. Flowering and senescence led to overall improved combustion quality, where flowered genotypes tended toward lower P, K, Cl, and moisture contents; marginally less, or similar, N, Si, and ash contents; and a similar HHV, compared to those miscanthus genotypes that did not flower.

Senescence is of paramount importance not only for downward nutrient translocation, and thus for stand longevity, but also because leaf-to-stem ratio tends to decrease. Leaves are much richer in ash, minerals, and alkali than stems, thus a feedstock with lower leaf proportion at harvest raises its quality for thermochemical conversion (Monti et al., 2008).

Stand age also affects cell wall composition within the same genotype. It has been shown that in a long-term stand of *Phalaris acquatica*, cellulose and lignin increased in the subsequent growth years after the establishment, while hemicellulose showed small but significant decreases as species became physiologically mature (Pappas et al., 2014). The loss of hemicellulose in mature stands has been associated with increased deposition of cellulose and lignin, or the replacement of hemicellulose in the cell matrix by lignin (Allison et al., 2012).

7.3 Bioconversion Processes

Lignocellulosic perennial grasses for energy application can be converted via either thermochemical or biochemical conversion pathways to produce heat, energy, liquid and gaseous biofuels, intermediates carriers, and by-products. In nonenergy applications, physical, chemical, or biological processes can be applied. In Fig. 7.2, the most widely used bioconversion processes and pathways, primary products, and by-products are displayed. Obviously, there are many other pathways to convert the lignocellulosic biomass that are currently under investigation by researchers and engineers worldwide.

In a bioenergy or nonenergy chain, the entire life cycles of both systems include cultivation, harvest and pretreatment, conditioning and logistics, conversion, use, and end of life (Schmidt et al., 2015). Independently of the field practices and bioconversion pathways applied, a biomass feedstock must be determined for its moisture content and bulk density at harvest, which in turn influences logistics options such as transport, conditioning, and storage (McKendry, 2002).

As shown before, moisture at harvest is highly variable among perennial grasses, with giant reed and bamboo typically wetter than switchgrass, miscanthus, and reed canary grass. Nonetheless, field practices (e.g., harvest time) and environmental conditions strongly influence moisture at harvest (Monti et al., 2015).

The bulk density of herbaceous biomass is generally lower as compared with woody species (McKendry, 2002). Measurement procedures can also affect bulk density values. Scordia et al. (2016) showed that the bulk density, measured as

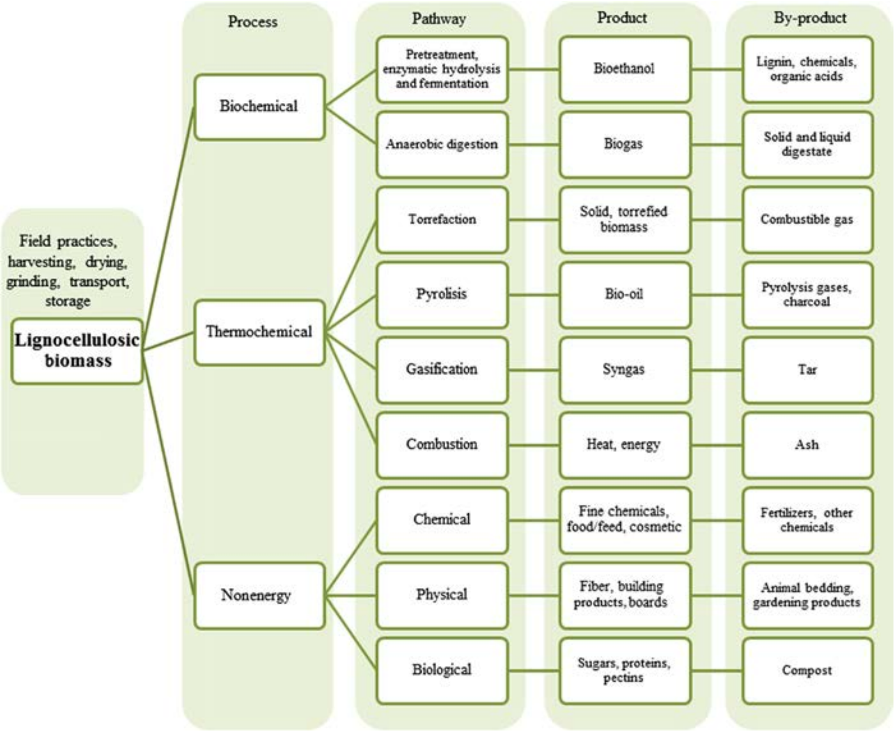

Figure 7.2 Energy and nonenergy applications of perennial grasses. Main bioconversion processes and pathways leading to primary products and by-products.

stacked biomass, was 169–297 kg m^{-3} in giant reed and 113–125 kg m^{-3} in miscanthus. Measurement employing random biomass decreased the bulk density by 49%–70% in giant reed and by 65%–70% in miscanthus. The low density of perennial grasses can increase costs of transportation, storage, and handling (Ryu et al., 2006). However, moisture and bulk density can be improved directly in the field by, for example, modulating harvesting time, field drying, and bailing the biomass, as reported for miscanthus and giant reed (Nolan et al., 2009; Pari et al., 2015).

In the following sections, the main bioconversion processes at the biorefinery plant gate will be separately discussed.

7.3.1 Biochemical Conversions

In biochemical processes, selected microorganisms (yeasts and/or bacteria) and/or macromolecular biological catalysts (enzymes) are employed to produce either intermediates (e.g., soluble sugars, organic acids, etc.) and/or final products (e.g., bioethanol, biomethane, etc.). Worldwide studied processes include second-generation bioethanol (2GB) and anaerobic digestion (AD).

7.3.1.1 Second-Generation Bioethanol

2GB is produced primarily from structural components of lignocellulosic crops (Hicks, 2007). Second-generation technologies have been developed because first-generation ones (i.e., from oil, sugar, and starch crops) have important limitations: there is a threshold above which they cannot produce enough biofuel without threatening food supplies, arable lands, and biodiversity (EU 1513/2015).

The technology to transform lignocellulosic material into bioethanol includes biomass pretreatment, enzymatic hydrolysis of cellulose, alcoholic fermentation of both hemicellulose- and cellulose-derived sugars, and distillation to upgrade ethanol concentration (Fig. 7.3). The majority of pretreatment methods involve a combination of mechanical size reduction, alkali swelling, acid hydrolysis, steam, and other fiber explosion techniques. Many different pretreatment approaches have been designed and tested, and some processes have also been tried on a pilot/demonstration scale. Ideally, the most desirable method of treatment is the dissolution of solid materials (e.g., hemicellulose and cellulose) into an aqueous substrate.

Pretreatment aims to catalyze the hydrolysis of hemicelluloses, decrystallize cellulose, and displace lignin structure (Scordia et al., 2011). Among pretreatment technologies, alkaline (NaOH or NH_3) or neutral pH methods (liquid hot water) remove hemicellulose as oligomers, while low pH methods, such as dilute acids pretreatment (either mineral or organic), remove hemicellulose as monomers, the ratios of which are dependent on the severity of the pretreatment (temperature, reaction time, and acid concentration) (Scordia

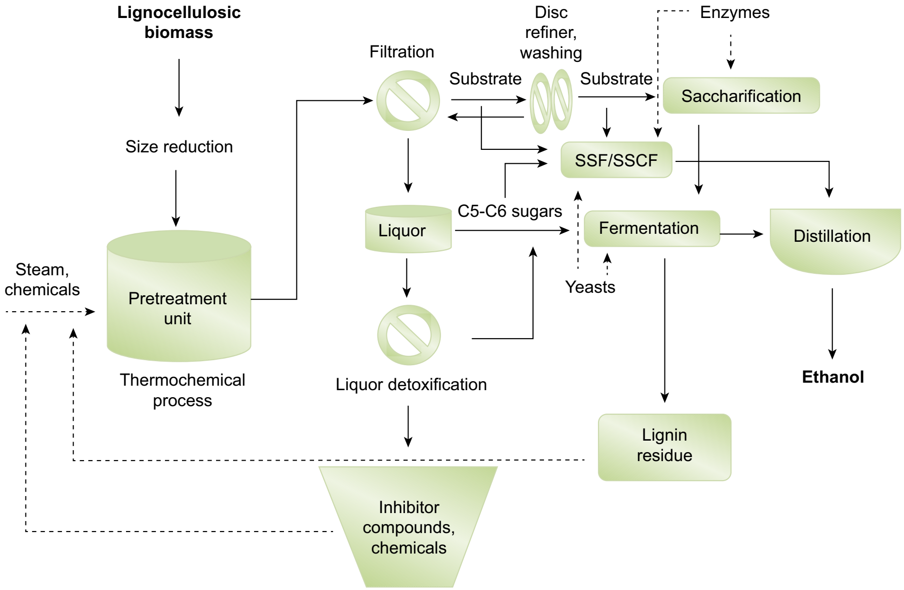

Figure 7.3 Diagram flow of lignocellulosic bioethanol production (2GB). *SSCF*, simultaneous saccharification and co-fermentation; *SSF*, simultaneous saccharification and fermentation.

et al., 2010). Pretreatments are typically conducted under pressure (from ambient to 4.8 MPa), temperature (from ambient to 270°C), and reaction times (from a few seconds to a few days), usually in high-pressure stainless steel vessels (bioreactors). The higher the pressure and temperature, the lower the reaction time, and vice versa.

Following pretreatment, two different fractions are recovered: a water-soluble fraction (i.e., hemicellulose-derived sugars) and a solid residue (i.e., cellulose and lignin). While the former can be directly fermented by microorganisms capable of using both hemicelluloses and cellulose-derived sugars, as, for example, *Pichia stipitis*, one of the most robust xylose-fermenting yeasts (Jeffries, 2006), the solid residue must undergo hydrolysis of cellulose to glucose by a cooperative action of three cellulase enzymes: (1) endo-1,4-β-glucanase; (2) exo-1,4-β-glucanase; and (3) β-glucosidase. Endoglucanase acts in a random fashion on the regions of low crystallinity on the cellulosic fiber, whereas exoglucanase removes cellobiose synergistically from nonreducing ends of cellulose chains. Finally, β-glucosidase not only produces glucose from cellobiose, but also reduces cellobiose inhibition (Henrissat et al., 1985). Optimal temperature for enzymes is between 45 and 50°C, with pH 4.8–5.0 and reaction time 12–96 h. The result is a glucose-enriched medium ready for alcoholic fermentation by ethanol-producing microorganisms.

One of the most successful methods was the combination of the enzymatic hydrolysis of pretreated biomass and fermentation in one step, termed simultaneous saccharification and fermentation (Wright et al., 1988). In this process, the glucose produced by the hydrolyzing enzymes is consumed immediately by the fermenting microorganism present in the culture, avoiding inhibitory effects of cellobiose and glucose to the enzymes by keeping a low concentration of these sugars in the media (Eklund and Zacchi, 1995). It is also possible to perform a cosimultaneous saccharification and fermentation, where both cellulase and hemicellulase enzymes are added with xylose/glucose fermenting yeast in one step (Taherzadeh and Karimi, 2007).

Perennial grasses have been successfully converted into 2GB. Scordia et al. (2011, 2012; 2013a) used giant reed as a raw material in an oxalic acid pretreatment at different temperatures, acid concentrations, and reaction times. Both C5 and C6 sugars were fermented into ethanol by *P. stipitis* CBS 6054 yeast strain, with a maximum theoretical ethanol yield of 75% for C6 and a C5 ethanol yield of 0.33 $g_{ethanol}/g_{sugar}$. The same process was employed for *M.* × *giganteus*, reaching a C5 ethanol yield of 0.38 $g_{ethanol}/g_{sugar}$, and maximum ethanol concentration from C6 of 20.2 $g\,L^{-1}$ with a volumetric ethanol productivity of 0.28 $g\,L^{-1}\,h^{-1}$ (Scordia et al., 2013b). Switchgrass, reed canary grass, and bamboo have been extensively used as raw material for 2GB production with interesting results (Mitchell et al., 2012; Kallioinen et al., 2012; Kuttiraja et al., 2013).

By-products that can be recovered at different process stages include the unhydrolyzed lignin, along with chemicals, organic compounds (i.e., acetic acid, hydroxymethylfurfural, furfural, levulinic and formic acids), and phenolic compounds (Palmqvist and Hahn-Hägerdal, 2000).

7.3.1.2 Anaerobic Digestion

AD is one of the most mature technologies for gaseous biofuel production, employing a broad variety of substrates, such as organic wastes, sludge, manure, and a wide range of crops and residues. In this process, bacteria break down biodegradable material in the absence of oxygen. Hydrolytic bacteria break down organic molecules into smaller soluble derivatives, such as simple sugars, amino acids, and fatty acids, that will serve as substrate for other bacteria. Acidogenic bacteria then convert soluble derivatives into CO_2, H_2, NH_3, and organic acids. The resulting organic acids are converted into acetic acid, along with additional CO_2, H_2, and NH_3. Finally, methanogenic bacteria convert these products into CH_4 and CO_2 (Sengupta and Pike, 2013). A by-product of AD is the digestate, a solid fraction not used by bacteria, that consists of mineralized elements, undigested cellulose, lignin, and dead bacteria. The material resembles domestic compost and can be used as such, or to make low-grade building products, such as fiberboard (Sengupta and Pike, 2013). Another by-product is a liquid, rich in nutrients, that can be used as a fertilizer; however, levels of potentially toxic elements should be assessed before use (Sengupta and Pike, 2013) (Fig. 7.4).

Currently, AD mostly relies on the codigestion of maize and animal slurries (Bauer et al., 2010; Herrmann and Rath, 2012). In the AD of lignocellulosic materials, hydrolysis may be constrained by high lignin content and crystalline cellulose, resulting in low methane output. Hence pretreatments, as described for 2GB, might be envisaged. In this regard, Di Girolamo et al. (2013) showed that untreated giant reed biomass exhibited a potential CH_4 yield of 273 mL g^{-1} VS; four pretreatments without acid catalyst achieved a 4%–23% CH_4 yield gain, while pretreatments with H_2SO_4 as catalyst incurred a methanogenic inhibition.

It has been reported that in the AD process with lignocellulosic material, harvest time significantly influences biomass digestibility and methane yields. Ragaglini et al.

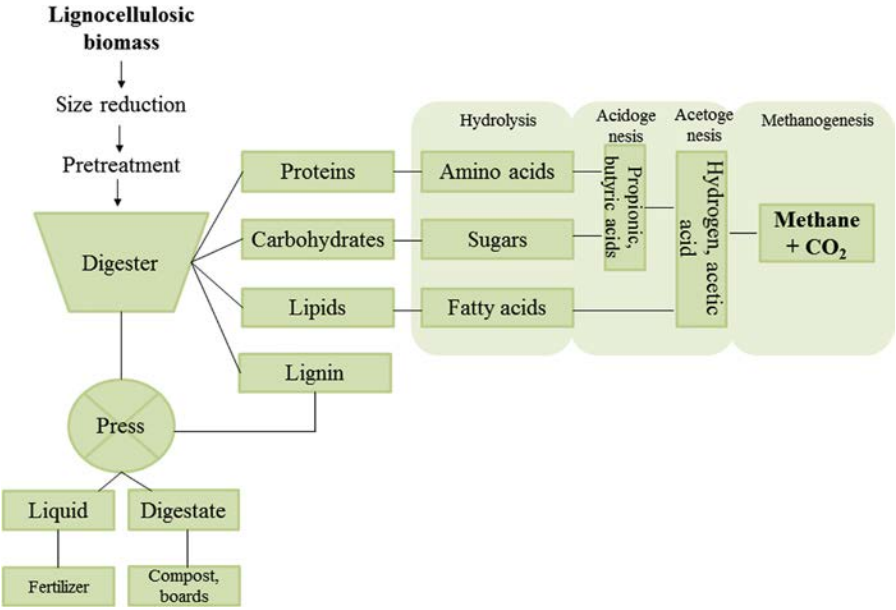

Figure 7.4 Diagram flow of lignocellulosic anaerobic digestion.

(2014) discovered that giant reed, although yielding more biomass in a single harvest per year, increased the CH_4 yield per hectare by 20%–35% when it was harvested two times per year (9452 and 11,585–12,981 Nm^3 CH_4 ha^{-1}, respectively), as a consequence of the highest biochemical methane potential achievable by juvenile stages of the crop, and a better digestion kinetics due to a lower biomass recalcitrance.

Similar results were reported by Kiesel et al. (2017) with five miscanthus genotypes, grown at three locations in six harvest dates. Although genotypes, location, and harvest time were significant on AD, generally, green harvest (as early sampling in August) improved the net energy yield of AD due to a combination of biomass yield per hectare and substrate-specific methane yield (e.g., organic and inorganic compounds in the biomass).

In a 2-year experimental trial, Kiesel et al. (2016) showed that methane yield (m^3 CH_4 ha^{-1} yr^{-1}) of maize, switchgrass, and miscanthus was strongly affected by the biomass dry matter yield at harvest. Maize overyielded both switchgrass and miscanthus in the most productive growing season; however, averaged across the 2 years, miscanthus methane yield was 4774 m^3 CH_4 ha^{-1} yr^{-1}, followed by maize at 4623 m^3 CH_4 ha^{-1} yr^{-1}, with switchgrass the least productive at 2711 m^3 CH_4 ha^{-1} yr^{-1}.

7.3.2 Thermochemical Processes

Thermochemical processes involve heat and oxygen as main reagents with the solid biomass to produce a number of primary products and by-products. In the following sections, the main thermochemical processes are discussed. Most of the process description and parameters (i.e., torrefaction, pyrolysis, gasification) come from the Biomass Technology Group BV (BTG), the Netherlands.

7.3.2.1 Torrefaction

Torrefaction is a thermal process to convert biomass into a coal-like material, which has better fuel characteristics than the original biomass. Torrefied biomass is more brittle, making grinding easier and less energy intensive. Compared to fresh biomass, storage of the torrefied material can be substantially simplified since biological degradation and water uptake are minimized.

Torrefaction involves the heating of biomass in the absence of oxygen to a temperature between 200 and 400°C. The structure of the biomass changes in such a way that the material becomes brittle and more hydrophobic. Although weight loss is about 30%, energy loss is only 10%. The main product is the solid, torrefied biomass. During the torrefaction process, a combustible gas is released, which is utilized to provide heat to the process (Fig. 7.5).

In BTG’s torrefaction concept, the heat required is generated by combustion of the vapors that are released in the process. For this purpose, the gases are directed to a dedicated combustion chamber, in which the combustion takes place at sufficiently high temperatures. The hot flue gas from the combustion is forced along the wall of the reactor to indirectly heat the biomass. Depending on the feedstock and required product quality, excess heat can be generated (e.g., for drying purposes or electricity production).

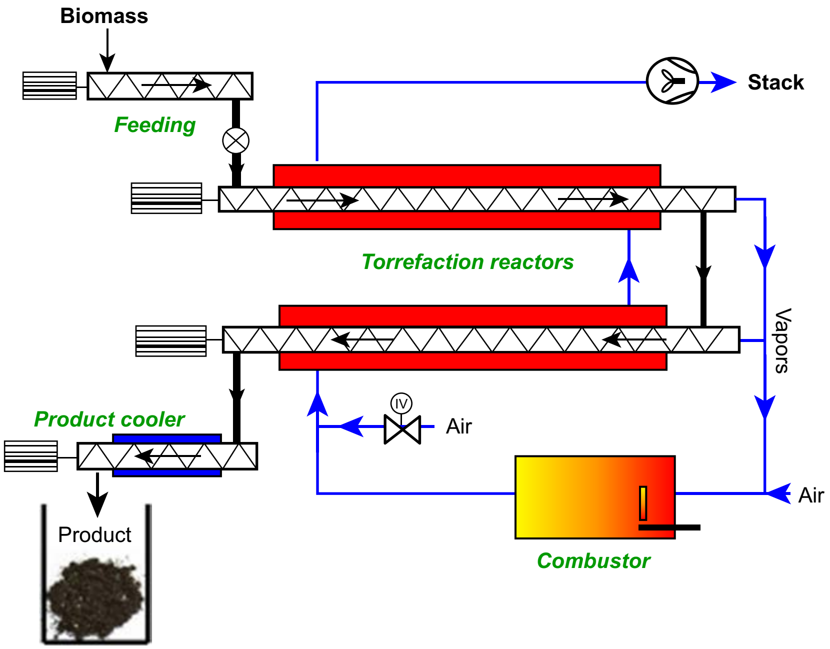

Figure 7.5 Diagram flow of Biomass Technology Group BV torrefaction using lignocellulosic feedstocks (http://www.btgworld.com/en/rtd/technologies/torrefaction).

All kinds of biomasses and residues can be converted in the torrefaction process, even very low-density materials (e.g., straw).

The product obtained in the process strongly depends on the applied process conditions. In BTG's process, the operating temperature and residence time can be easily varied to obtain products of a different quality (bioenergy, biochar, specialties such as activated carbon). At high temperatures, a completely carbonized material is produced.

In the framework of the OPTIMA project (FP7 289642, 2015), BTG fed the torrefaction pilot unit with giant reed and *M.* × *giganteus* as feedstock under a reaction temperature of 280°C. The retained chars in the solid product for giant reed and miscanthus were 69% and 74%, respectively, with an energy yield of 90% and 87%, respectively (private communication, D. van den Berg). These results are in line with the retained char of 70%–80% of larch, willow, beech, and straw under 280°C (Prins et al., 2006).

Torrefaction can be also used as pretreatment for higher-temperature processes, such as gasification or cofiring. For example, Xue et al. (2014), torrefied *M.*×*giganteus* at temperatures from 230 to 290°C, obtaining a biomass with reduced water and hemicellulose content, a lower C—O ratio, and a more porous structure with larger specific surface area.

7.3.2.2 Pyrolysis

Pyrolysis is a process in which organic materials are rapidly heated in the absence of air. BTG uses fast pyrolysis technologies at temperature ranges of 450–600°C.

Under these conditions, organic vapors, pyrolysis gases, and charcoal are produced. The vapors are condensed into a clean liquid bio-oil, an intermediate suitable for a wide variety of applications. Typically, 60–75%w/w of the feedstock is converted into bio-oil. BTG's fast pyrolysis process is based on the rotating cone reactor. Biomass particles are fed near the bottom of the pyrolysis reactor together with an excess flow of hot heat carrier material such as sand, where it is pyrolyzed. The produced vapors pass through several cyclones before entering the condenser, in which the vapors are quenched by recirculated oil. The pyrolysis reactor is integrated in a circulating sand system composed of a riser, a fluidized-bed char combustor, the pyrolysis reactor, and a downcomer. In this concept, char is burned with air to provide the heat required for the pyrolysis process. Oil is the main product; noncondensable pyrolysis gases are combusted and can be used, for example, to generate additional steam. Excess heat can be used for drying the feedstock (Fig. 7.6).

Due to the presence of large amounts of oxygenated components, the oil has a polar nature and does not mix readily with hydrocarbons. The degradation products from the biomass constituents include organic acids (such as formic and acetic acid), giving the oil its low pH. Water is an integral part of the single-phase chemical solution. The (hydrophilic) bio-oils have water contents of typically 15–35%w/w. Typically, phase separation does occur when the water content is higher than about 30%–45%.

In the framework of the OPTIMA project (FP7 289642, 2015), BTG fed the fast pyrolysis pilot unit with giant reed and miscanthus as feedstock under a reaction

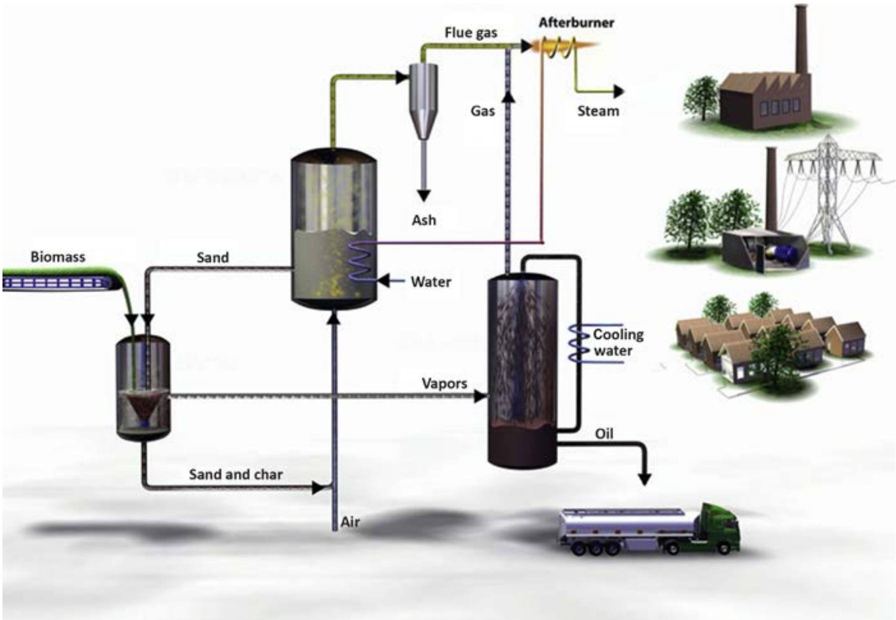

Figure 7.6 Diagram flow of Biomass Technology Group BV fast pyrolysis using lignocellulosic feedstocks (http://www.btgworld.com/en/rtd/technologies/fast-pyrolysis).

temperature of 520–529°C. Miscanthus yielded more liquid than giant reed (63% vs. 55%), with higher energy and carbon yield as well. Typically, pyrolysis of wood yields 60%–65% liquids, which is comparable to miscanthus (private communication, D. van den Berg). Giant reed showed a lower yield than miscanthus due to higher biomass ash content (5.6% vs. 3.4%), as ash cannot be converted into pyrolysis oil, but even more so because of the catalytic effect ash components play in the pyrolysis process.

7.3.2.3 Gasification

In BTG's two-stage gasification technology, biomass is fed to the fast pyrolysis reactor, where organic vapors are produced. Whereas in the pyrolysis process the vapors are condensed, in the two-stage gasifier the vapors are reformed into a clean fuel gas. In the top section of the "gasifier" the vapors are mixed with (preheated) air to increase the temperature to 800–950°C. The bottom part can be filled with a reforming catalyst to convert remaining tar and ammonia. In the last stage the gas is cooled to ambient. An overall cold-gas efficiency in the range of 65%–80% is expected (Fig. 7.7).

Gasification with perennial grasses needs careful consideration due to potential ash sintering. The initial deformation temperature of perennial grasses shows great variability among species, with giant reed ranging between 823 and 1200°C, *M.×giganteus* 1020°C, and *M. sinensis* 1190°C (Scordia et al., 2016), as compared to 1450–1515°C for wood (Ragland et al., 1991).

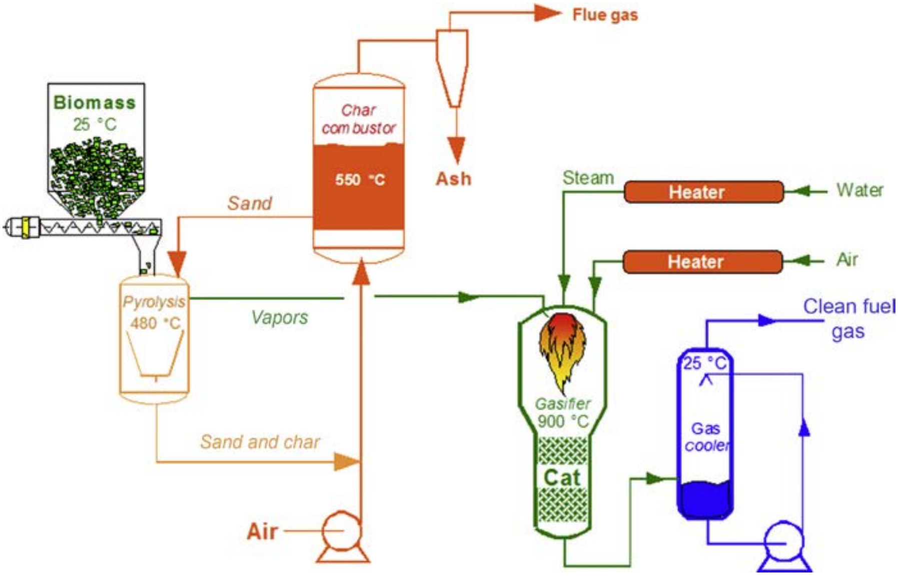

Figure 7.7 Diagram flow of Biomass Technology Group BV gasification using lignocellulosic feedstocks (http://www.btgworld.com/en/rtd/technologies/gasification).

7.3.2.4 Combustion

Combustion is the oldest thermochemical process used by humanity to produce heat before the advent of fossil fuel. Historically, biomass combustion systems have been designed around wood, thus substituting grasses would not produce satisfactory results. In the process of combustion, the solid biomass (moisture content <20%) and oxygen (12%–15%) are combined in a high-temperature environment (700–1300°C) to form carbon dioxide, water vapor, and heat. To ensure that combustion is as efficient as possible, it is essential to maximize temperature, time, and turbulence simultaneously (Overend, 2009).

The most efficient combustion system would fully complete the combustion before transferring the heat to the boiler and turbines. The end result of combustion is useful energy—typically in the form of heat and power, or both combined heat and power. Most ash from combustion remains in the combustor and must be removed.

Biomass should undergo sizing and drying to reach a moisture content as low as possible, ideally lower than 20%. Biomass densification (e.g., pellet, briquette, bailing, etc.) could also be applied to increase bulk density and standardize feedstock properties.

As combustion temperatures are generally higher than any other thermochemical process, ash, mineral, and alkali content should be determined. Furthermore, the ash-melting behavior, alkali index, fouling index, and slagging index would be good predictors of the biomass quality for combustion purposes (Jenkins et al., 1998).

For instance, it is widely accepted that a feedstock with a slagging index lower than 1150°C has a severe potential, from 1150 to 1230°C a high potential, from 1230 to 1340°C a medium potential, and greater than 1340°C a weak slagging potential. Scordia et al. (2016) evaluated the slagging index of three giant reed clones, *M.*×*giganteus* and *M. sinensis*. It was found that perennial grasses were either characterized by a slagging index slightly higher than 1200°C (one clone of giant reed and *M. sinensis*) or lower than 1150°C (two clones of giant reed and *M.*×*giganteus*), therefore with high or severe slagging propensity, respectively.

The alkali index (kg K_2O and Na_2O per GJ energy) expresses the fouling propensity of a feedstock; with an alkali index above $0.17\,\mathrm{kg\,GJ^{-1}}$, fouling is probable, and above $0.34\,\mathrm{kg\,GJ^{-1}}$ it is almost certain (Tanger et al., 2013). Miles et al. (1995) reported an alkali index in switchgrass between 0.30 and 1.41, in miscanthus between 0.45 and 0.78, and in giant reed it was 1.29.

The unfavorable slagging and alkali index might limit the use of perennial grasses under conversion operating at high temperatures, such as gasification and combustion. Thus careful feedstock evaluation must be done before use.

7.3.3 Nonenergy Application

In nonenergy biomass uses, physical, chemical, or biological processes can be applied. Nonenergy application includes the whole use of biomass after harvest, or the use of intermediate after a primary conversion, or the biomass residue at the end of the process.

Perennial grasses for nonenergy application include nonwood fiber for papermaking, building material, phonic insulating material, mulching and biodegradable products for gardening and animal bedding, soil organic fertilizer, and green chemistry products, among others (Fig. 7.8).

Biomass for nonenergy application is steadily growing as a slipstream of the promotion of the biobased economy. For instance, the worldwide production capacity for biobased polymers grew by 4% from 2015 to 2016, representing a share of 2% of the global polymer market and a turnover of about €13 billion. Production capacity of biobased polymers is forecast to increase from 6.6 million tons in 2016 to

Figure 7.8 Nonenergy application materials from *Miscanthus* spp.
From the "Perennial Biomass Crops for a Resource Constrained World" conference, University of Hohenheim, Stuttgart, Germany, September, 7–10 2015. Photo by Danilo Scordia.

8.5 million tons by 2021 (nova-Institut GmbH; www.nova-institut.eu). Some examples of nonenergy applications are reported in the following sections.

7.3.3.1 Nonwood Papermaking

The use of perennial grasses for papermaking is not new. For instance, the history of giant reed for nonwood papermaking started in 1830 (Perdue, 1958). From 1930 to 1950 the pulping and bleaching ability of giant reed was investigated with satisfactory strength properties and bleachability (Bhat and Virmani, 1951; Di Felippo, 1955).

Shatalov and Pereira (2006) used organosolv pulping technologies in combination with totally chlorine-free bleaching for papermaking of giant reed fiber. The authors found that giant reed was poorer in fibers but richer in short parenchyma cells than woody species. Some differences in fiber dimension of nodes and internodes were also found. The fiber from internodes had equal length (1.2 mm), small diameter (14.6 vs. 16.9 µm), and cell wall thickness (4.6 vs. 5.3 µm) suggesting better papermaking properties as compared with fibers from nodes.

The average fiber length of giant reed is fairly close to *Eucalyptus globus* (0.7–1.3 mm) and resembles wheat straw (1.0 mm) and bagasse (1.0–1.5 mm). The fiber width is close to that reported for eucalyptus (13–19 µm), wheat straw, and corn stalks (15 and 18 µm, respectively) (Atchison, 1993). Even the fiber wall thickness does not vary from that of wood (2–8 µm), thus the strength properties are very close to those of leading wood and nonwood raw materials (as eucalypt and wheat straw, respectively).

7.3.3.2 Building Material

In the building industry, plant fibers have been used for centuries. In the last few decades there is a growing interest in a “modern update” of those “old” applications. Especially fiber-rich plants, such as hemp, flax, and kenaf, are investigated; however, perennial grasses also deserve attention. In this process, the fibers are added to the concrete or mixed with polymers to add new characteristics to the material.

From 1992, demonstration projects investigated the feasibility of miscanthus for the production of panel boards and building blocks in Europe (Mangan, 1994; Visser and Pignatelli, 2001) and the production of medium-density fiberboard (MDF). Harvey and Hutchens (1995) found that MDF boards made from miscanthus were comparable with those made from woodchips.

Light natural sandwich materials (LNS) were designed to plane and mold structural parts with high form stability and low weight for a broad range of applications, such as substitute sandwich material made with plastic, fiberboards, particle boards, insulating material, etc. LNS consist of wooden upper and lower outer layers and a core of evenly oriented hallow plant stalks, which are bonded with a natural adhesive (e.g., gluten foam). The core material can be made up from a number of different plant species with high-strength stalks, i.e., perennial grasses, ensuring a high-quality product (FAIR CT983784, 2001).

7.3.3.3 Bedding Material and Mulching

A lying surface (mattress and bedding) for domesticated animal is one of the most cost-efficient measures for optimizing health and welfare (Bruijnis et al., 2013). Factors that can influence lying time include dry matter content, water-holding capacity, and particle size of the bedding material, but also the presence of a sufficient amount of bedding.

Van Weyenberg et al. (2015) investigated *M.* × *giganteus* to replace straw in deep dairy cow cubicles. The authors concluded that no significant differences were found in bacterial growth, dust concentration, the capacity of the material to remain in the cubicles, skin lesions, and cleanliness score of the cows, as well as two indices for cow comfort. Thus given the aforementioned quality of miscanthus, and the well-known superior biomass yield, this species is suitable for replacing agricultural straws in animal bedding applications.

As a mulching material, switchgrass pellets and chopped miscanthus were investigated against wood mulch and composted sawdust for efficacy in weed suppression. It was found that, although preliminary, the most consistent and favorable results belonged to the switchgrass pellets (0.14 weed m^{-2}) and chopped miscanthus (0.87 weed m^{-2}) on total number of weeds (Huber-Kidby, Ministry of Agriculture and Rural Affairs).

7.3.4 Other Applications

Biomass as a raw material, or as an intermediate of the primary energy processes, or even the primary product not used for energy application, can be the basis for a huge number of new products and chemicals (Fig. 7.9). Ideally, biomass should undergo a complete fractionation into the three major components, namely, hemicellulose, cellulose, and lignin, for maximum possible utilization. Pretreatments (see Section 7.3.1.1) allow the hydrolysis of hemicelluloses to xylose, mannose, galactose, and glucose, and acetic acid is also liberated from acetyl groups. Furthermore, cellulose decrystallization and displacement of lignin structure also takes place (Scordia et al., 2011).

At high temperature and pressure or severe acidic concentration, xylose is further degraded to furfural (Dunlop, 1948). Similarly, 5-hydroxymethyl furfural (HMF) is formed from hexose degradation (Ulbricht et al., 1984). Formic acid is formed from furfural and HMF breakdown, while levulinic acid is formed from HMF degradation (Dunlop, 1948; Ulbricht et al., 1984). Phenolic compounds are generated from partial breakdown of lignin (Sears et al., 1971; Lapierre et al., 1983; Bardet et al., 1985).

In the 2GB process such compounds inhibit microbial metabolism, hindering the bioconversion of sugars into desired products (Palmqvist and Hahn-Hägerdal, 2000). The amount of inhibitory compounds released depends on the severity of the pretreatment, while the microbial inhibition depends on the type and concentration of the inhibiting compounds (Larsson et al., 1999).

Inhibitory compounds can be either minimized through pretreatment optimization (i.e., reaction temperature, pressure, time, and catalyst concentration) or by employing detoxification methods, such as pH adjustment, active charcoal adsorption,

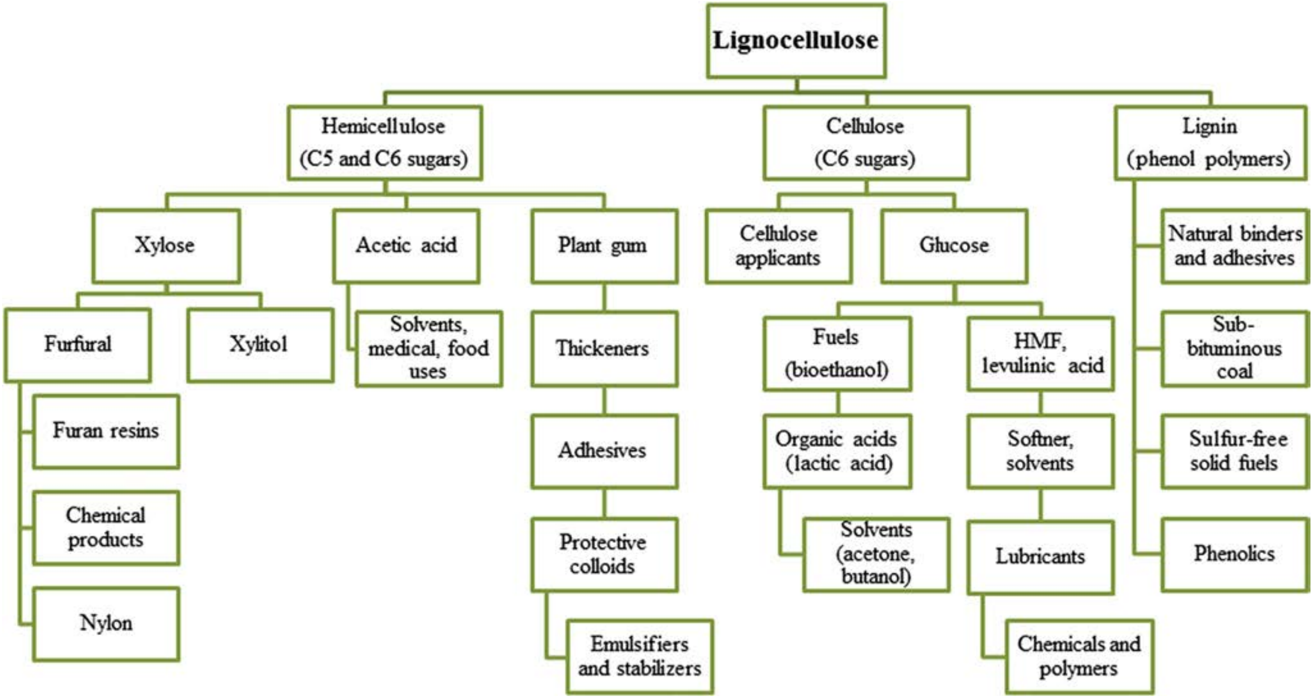

Figure 7.9 Alternative applications of lignocellulosic biomass.
Modified from Kamm, B., Gruber, P.R., Kamm, M., 2008. Biorefineries – Industrial Processes and Products: Status Quo and Future Directions. WILEY-VCH Verlag GmbH & Co. KGaA, ISBN: 978-3-52-761984-9.

ion-exchange resin adsorption, and biological abatement (Olsson and Hahn-Hägerdal, 1996; Nichols et al., 2010). According to some detoxification methods (e.g., electrodialysis), inhibitory compounds can be recovered (Lee et al., 2013) for a variety of potential uses, in turn increasing the lignocellulosic conversion revenues per ton of dry raw material (Kamm et al., 2008).

Scordia et al. (2012) showed that the main inhibitory compounds detected in giant reed water soluble fraction were acetic acid from the release of acetyl groups from acetylated xylan, furfural from pentose degradation, HMF from hexose degradation, and phenolic compounds from lignin degradation. Acetic acid, furfural, HMF, and total phenolic compounds increased as the severity of the pretreatment rose (severity factor (SF), combination of temperature and time), and also increased with acid concentration [oxalic acid (OA)] when SF was held constant. The lowest values for degradation products were found at 2.93 SF and 3.21% OA concentration: 2.80, 0.61, 0.46, and 4.60 ($g\,L^{-1}$) against the highest values at 4.05 SF and 5.0% OA concentration: 11.0, 7.57, 1.48, and 7.37 ($g\,L^{-1}$) for acetic acid, furfural, HMF, and total phenolic compounds, respectively.

In *M.* × *giganteus*, acetic acid, furfural, HMF, and total phenolic compounds reached 9.0, 9.4, 0.75, and 7.92 ($g\,L^{-1}$) at the highest pretreatment severity and OA concentration used during pretreatment (Scordia et al., 2013b).

Other potential routes to produce biomaterials and chemicals from intermediate or primary products have been explored. For instance, BTG is developing different new products by using pyrolysis oil as the raw material. Examples of these are: (1) pyrolytic lignin as a substitute for fossil phenol in phenol/formaldehyde resins; (2) pyrolytic lignin as a replacement for fossil bitumen; (3) recovery of organic acids; (4) production of monophenolics; (5) pyrolytic sugars for green chemistry and biofuels; and (6) pyrolysis oil fractionation for other uses.

As pyrolysis oil is a mixture of cracked components originating from cellulose, hemicellulose, and lignin, this oil can easily be fractionated into three product streams: pyrolytic lignin (from lignin), pyrolytic sugars (from cellulose), and a watery phase containing smaller organic components, such as acetic acid (mainly from hemicellulose). In the BTG pilot plant, pyrolytic lignin typically yields 20–30%w/w with a water content of about 10–11%w/w. The pyrolytic lignin showed to be a potential substituent for fossil phenol in phenol/formaldehyde resins. These types of resins are widely used in wood products such as particle boards and plywood. It has been demonstrated that the phenol in phenol/formaldehyde resins can be substituted up to 75%w/w by pyrolytic lignin and still meet the D4 (NEN-EN 204/205) standards for this type of resin. Another interesting application of pyrolytic lignin is in the replacement of fossil bitumen in various bitumen-based materials, such as in asphalt. In addition, pyrolytic lignin could be used in the production of green phenolic (mono-) derivatives, as a possible raw material for various coatings, composites, and preservatives.

Subsequently, sugars and small organics can be extracted from the remaining bio-oil after pyrolytic lignin separation. The pyrolytic sugar phase, containing high amounts of levoglucosan, cellobiosan, and larger sugar molecules, can be concentrated to obtain a thick syrup (up to 30%w/w of the original oil). This sugar might enter the renewable sugar platform to produce bioethanol, levulinic acid, polyols, and other compounds.

From the last fraction, the water phase, acetic acid can be produced by means of an extraction step followed by simple distillation (Mahfud et al., 2008; Rasrendra et al., 2011). In this way, an acetic acid stream with a concentration up to 90%w/w can be produced. Applications of this acetic acid could be, for example, in the production of solvents and foods, and for medical use.

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Sustainability of Perennial Crops Production for Bioenergy and Bioproducts

8

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8.1 Introduction

To make available sufficient primary energy sources and secondary energy forms to meet the needs of society is a global issue and is receiving attention toward its sustainability (environmental, economic and socioeconomic). Most of the energy supply is based on fossil resources, which are finite, nonrenewable, and their use raises serious environmental concerns. In fact, the known viable reserves of petroleum, coal, and natural gas are being depleted at a fast rate and its combustion generates greenhouse gas emissions and other pollutants, such as sulfur dioxide, volatile organic compounds, and heavy metals (Nicoletti et al., 2015). Fossil resources also provide raw materials, such as olefins and aromatics, for the production of a multitude of complex materials, such as solvents, detergents, adhesives, plastics, resins, fibers, elastomers, and lubricants. Therefore searching for new energy and materials resources to optimize the supply structure has become an important step to prevent energy shortage, climate change, and nonrenewable materials depletion.

Biomass represents a renewable source of energy and materials, since it is naturally replenished on a human timescale. Through the process of photosynthesis, sunlight energy can be fixed and stored in plants or microalgae as sugars, and thereafter the produced biomass can be converted into solid, liquid, or gaseous biofuels, heat, or biobased products. Moreover, biomass and the products derived from it are compatible with existing systems and are biodegradable. Perennial grasses, such as *Miscanthus* spp. and *Arundo donax* (L.), have been recognized as low-cost and low-maintenance crops and the high-yielding biomass can be used for the production of energy (for both solid and second-generation biofuels), paper pulp, and biomaterials (Alexopoulou et al., 2011, 2012, 2013). Their great production potential lies in their low production costs, relatively low water needs, lower-energy input requirements (fertilizers, pesticides, etc.), and positive environmental impacts (e.g., potential as carbon sink and remediation and filter systems, with high water and nitrogen use efficiencies) (Cosentino et al., 2012; Zegada-Lizarazu et al., 2010). Yet the increasing demand for biomass raises the competition for agricultural land, accentuating the fuel versus food dilemma and the land use change debate (Dauber et al., 2012).

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Furthermore, to meet the biomass procurement, environmental sustainability can be questioned due to the intensiveness of the cultivation and the increased pressure on natural resources.

This chapter provides a comprehensive review of studies on the sustainability of perennial grass production and utilization, focusing on environmental, economic, and socioeconomic impacts. In this work, data retrieved from literature was supplemented with results obtained from the OPTIMA project (Optimization of Perennial Grasses for Biomass Production—2011–2015, funded by the European Union; www.optimafp7.eu). In addition, through an integrated approach, options for preventing disadvantages and strengthening advantages are indicated to provide new insights into the future development of these crops in a sustainable agriculture context.

8.2 Methodological Aspects

8.2.1 Life Cycle Assessment

Life cycle assessment (LCA) is an environmental management tool and addresses the environmental aspects and potential environmental impacts (e.g., use of resources and the environmental consequences of emissions) of a product (any good or service). A wide range of impact categories is covered, providing a comprehensive picture of the product's environmental implications. The assessment includes the product's entire life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal. The approach is therefore often called cradle-to-grave, well-to-wheel (fuels), or farm-to-fork (food). This so-called life cycle thinking helps to avoid a shifting of environmental burdens between life cycle stages, between geographical regions, or between impact categories.

LCA is internationally standardized through ISO standards 14040:2006 and 14044:2006 (ISO, 2006a,b) and can among others assist in:

- identifying opportunities to improve the environmental performance of products at various points in their life cycle and
- informing decision-makers in industry, government, or nongovernment organizations (e.g., for the purpose of strategic planning, priority setting, product, or process design).

The aforementioned ISO standards define four phases in an LCA study (Fig. 8.1).

The ISO 14040 and 14044 standards provide the indispensable framework for LCA. This framework, however, leaves the individual practitioner with a range of choices, which can affect the legitimacy of the results of an LCA study. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to ensure consistent and high-quality LCA studies. However, each attempt to increase comparability (e.g., through further standardization) inevitably decreases flexibility. One example for further standardization of LCAs is the International Reference Life Cycle Data System (ILCD) (JRC-IES, 2012). The ILCD Handbook is a series of technical documents that provide detailed guidance on all steps required to conduct an LCA. It also specifies in which decision context flexibility or strictness regarding these rules is more important.

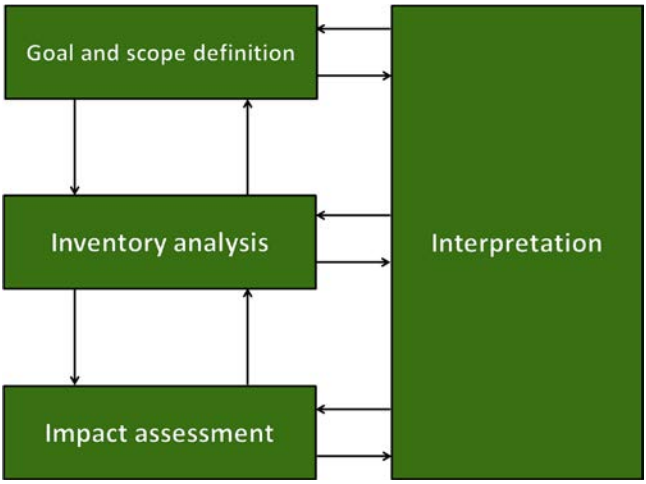


Figure 8.1 Illustration of the four phases of a life cycle assessment (according to ISO, 2006a,b).

Box 8.1 Examples on Impact Categories Used in Life Cycle Assessment

- Climate change
- Ozone depletion
- Human toxicity
- Respiratory inorganics (particulate matter formation)
- Photochemical ozone formation
- Acidification
- Eutrophication
- Ecotoxicity
- Land use
- Resource depletion

The fourth phase of LCA, the so-called impact assessment, proceeds through four steps. The first two steps, the selection of impact categories and classification (1) and characterization (2), are mandatory. To provide a comprehensive picture of the product's environmental implications, usually a wide range of impact categories is covered (see Box 8.1). The following two steps, normalization (3) and weighting (4), however, are optional.

During normalization, the characterized impact scores are associated with a common reference, such as the impacts caused by one person during 1 year in a stated geographic context. This facilitates comparisons across impact categories.

During weighting, the different environmental impact categories are ranked according to their relative importance. Weighting may be applied when trade-off situations occur in LCAs that are being used for comparing alternative products. Weighting factors, however, cannot be entirely based on scientific facts but depend on personal value-based choices defined beforehand. Furthermore, trade-off situations do not become apparent and decisions regarding these conflicts depend on weighting factors, which are hard to understand for decision-makers not involved in the study.

Although well established and suitable for the assessment of global and supraregional environmental impacts, standard LCA methodology to date is not yet able to address local and site-specific impacts on environmental factors such as biodiversity, water, and soil. As long as methodological developments into this direction are still ongoing, classical LCA should be supplemented with an assessment of local and site-specific impacts based on elements borrowed from Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) (Fernando et al., 2010b, 2015b; Reinhardt and Cornelius, 2014; Rettenmaier et al., 2013).

8.2.2 *Environmental Impact Assessment*

EIA is an evaluation method to explore the possible environmental effects of a proposed project. EIA examines the anticipated environmental effects and determines the importance of these effects, in both the short and long term. It focuses on local environmental effects. Data are collected and evaluated on that level. The environmental impact analysis of crop production requires good knowledge of the cultivation operations, the requirements and the productivity of the various crops in different climates, soil types, and methods of cultivation. There is not a general list of criteria to assess the environmental impact nor a general description of methods to be used. Fixing the environmental criteria is part of the EIA process. Usually, criteria address emissions to soil, ground, and surface waters and air, effects on the living environment and health of people in the surroundings, effects on surrounding ecosystems, and effects on cultural assets (Biewinga and van der Bijl, 1996). Box 8.2 shows examples of criteria usually used in EIA.

Although EIA can be more descriptive, it is necessary to aggregate information to condense numerous inventory data into more comprehensible information about potential environmental impact. To facilitate a direct comparison, parameters can be normalized: translated into the same measure. A simple form of normalization can be used: all parameters are translated into a figure between 0 and 100, for example, with 0 being the lower impact and 100 the highest impact for each category (Fernando et al., 2010b). As a last step the scores on the different indicators can be weighted. Defining weighting factors is value-based pronouncement, which brings ambiguity and subjectivity to the study at hand. Some authors agree that, whenever applied, weighting should reflect the relative importance of the impact categories in the organizational context of the study (Schmidt and Sullivan, 2002). After the application of a weighting factor to each category, a weighted average final score for each crop can be estimated according to Eq. (8.1).

$$\text{Score}_{\text{crop}} = \frac{\sum \text{Score}_{\text{indicator}} \times \text{weight}_{\text{indicator}}}{\sum \text{weight}_{\text{indicator}}} \tag{8.1}$$

Box 8.2 Examples of Criteria Usually Used in Environmental Impact Assessment

- *Emission of minerals to soil, water and air*, an estimation of the amounts of minerals (N, P, K) applied to soil and their removal with the crop can show whether there is a mineral build-up in the soil or the reverse. Although high N, P, and K content of the soil favors soil fertility, there is the risk that an excess of plant-available nutrients in the soil may be lost through future leaching or erosion, an important fact regarding the long-term fertility of the soil and the eutrophication of soil and water.
- *Emission of pesticides*, concerning the quality of soil, ground and surface water, and air, one of the most serious problems is pollution by pesticides. The amount of emission is affected by the amount of pesticides used and characteristics of the pesticide.
- *Use of water resources*, the contribution of a crop to groundwater depletion and desiccation correlates with its water use.
- *Hydrology effects* of cultivation occur when the land use alters the flow of water as groundwater, stream water, runoff, transpiration, etc.
- *Use of mineral resources*, the use of mineral resources, i.e., withdrawal of materials from the environment, can lead to exhaustion. The use of phosphate and potash fertilizer, as a criterion for the exhaustion of fertilizer ores, can be assessed.
- *Soil erosion* is a serious kind of degradation since it is irreversible. Soil loss also means a loss of plant nutrients and organic matter, which can impair the land's productivity.
- *Soil organic matter* plays an important role in several ways. It helps to keep plant nutrients available, contributes to good soil structure, prevents erosion, and keeps soil moist.
- *Soil structure* is defined by the amount and distribution of pores. The pores are mainly filled with gas (air), water, and plant roots. Soil compaction, i.e., loss of pore space, makes soils less suited for plant production.
- *Soil pH*, a very important factor, controls many chemical and biological activities in the soil, for example, availability of plant nutrients and activity of soil microorganisms.
- *Waste production and utilization*, an inventory of waste products used and produced during biomass cropping can be performed. In a qualitative approach, each of them will be judged positively or negatively.
- *Biodiversity*, erasing diversified vegetation and replacing it with mono-cultural crops is always a violation against it, but the consequences appear as site-specific factors, such as the number of species affected by the cultivation.
- *Landscape*, the aesthetic value may be affected by the choice of the crops and cultivation systems. Two criteria can be considered: effects on the variation of structure and effect on variation of colors.

8.2.3 Economic Analysis of Crop Production

Economic analysis examines the profitability and financial sustainability of projects to assess the attractiveness of funding alternative investment opportunities. In particular, the economic examination of perennial crops requires the estimation of all costs and revenues generated in each and every year during the economic life of the examined crop and the necessary size and timing of the required investment.

Discounted cash flow methods (Kruschwitz and Loeffler, 2005) can be adopted for the investigation of multiannual crops because economic analysis needs to explore the economic behavior of such projects throughout their economic life (life cycle economic analysis (LCEA); Kulczycka and Smol, 2016).

Income and expenses of agricultural projects vary significantly from year to year due to the physical development of multiannual plantations and the changing needs and yields, which are specified by agronomic practices. Project *profitability* is calculated as the difference between income and expenses. Revenue is earned mainly from the sale of products and services. Expenses consist of categories such as human resources, machinery and equipment, raw materials, rented services (outsourcing), land rent, financial and tax expenses, etc. Income and expenses are not constant during the economic life of the plantations and as a result profitability varies from year to year. It is not uncommon for agricultural projects to suffer losses during the first years of the crop and enjoy good profits afterward, when the plantation is mature and yields are high. Usually, profitability values and indices are reported for mature plantations and are missing the accumulated losses during the early years, which are most important for the farmer or the entrepreneur.

Although *profitability metrics* are generally the most widely used and easily understood measures of performance, they do not offer the investor complete information, because they do not reveal vital cash inflow and outflow details, which might be most important. Analysis of the project *Cash Flows* is essential, especially for the purpose of capital budgeting and investment appraisal, when we need to compare the present value of net inflows to the invested amount, which is usually paid up front.

Due to the time value of money (Kruschwitz and Loeffler, 2005), the stream of costs and revenues of agricultural projects is difficult to compare with alternative opportunities with different cash flow patterns, unless money values are expressed in some common "denomination," e.g., present values. Discounting of future monetary flows (cash flows) is common in economic evaluation, because it allows the calculation of one value figure, the present value, which embodies the whole stream of cash flows.

In the methodological approach, each crop is examined for the whole of its useful life. To estimate costs, agricultural production is broken down into single operations or activities and the needs of each activity are identified and measured in terms of human or machine hours, volumes of raw materials consumed, rental, etc. The initial investment is separately identified and valued.

Farm accounts do not usually identify the full cost of agricultural production, probably due to lack of consensus and data on imputed costs, such as family labor, own land, etc. For economic analysis, these items should be estimated at their opportunity cost to identify the net income attributed to the project.

Economic methodology requires the decomposition of the project into a number of operations or activities, which sufficiently describe crop installment, cultivation, harvesting, and storage activities. Each operation is characterized by its timing (both duration per hectare and seasonality within each year) and its needs for land, labor, equipment, and materials. Seasonality is important if peak labor, machinery, and water needs have to be identified. Fuel consumption depends upon the type of operation and machinery used.

All cost items are first measured in physical quantities, for example, land area, labor and machine hours, liters of fuel, raw material volumes, etc. This provides a cost measurement system independent of prices of resources, at least in the short run. The required quantities of factors of production and raw materials are then multiplied by their corresponding prices to calculate the total cost in monetary terms.

Mechanical equipment may be hired, if own machinery is insufficient or nonexistent. When hired, its cost is equal to the rental paid. The annual cost of own equipment is the sum of depreciation, interest, maintenance, insurance, labor, and fuel. If divided by hours of operation per year, it gives an estimate of the hourly cost of the equipment.

Land is an essential factor of agricultural production and in most cases a major cost item. The cost of agricultural products may be significantly increased if planted on high-cost land and vice versa. Therefore land cost must be carefully estimated in all agricultural projects. If there is a fairly competitive market for land, one may assume that its rent adequately reflects its real cost. However, if there is no market, the cost of land is not easily identifiable. In such cases, one needs to estimate its opportunity cost as expressed by the net economic output of current or usual land use. Marginal land rent is much more difficult to estimate because its opportunity cost is very site specific (various degrees of marginality) and because of possible distorting subsidization.

Labor is usually provided by the farmer and his family, but it may also be hired, especially during peak labor demand, e.g., at planting or harvesting times. Hired labor in most cases has a market-specified rate, which can be used in the analysis. Imputed labor cost should be principally evaluated at its opportunity cost, i.e., the amount of income forgone for shifting family labor from current activity due to the needs and requirements of the project.

In general, when there is no market for a commodity, the opportunity cost of the relevant factor or production should be used to estimate the cost of inputs. Opportunity costs should reflect implicitly market values. For example, produced expendable inputs should be valued at the cost of purchasing the input from off-farm. Similarly, capital services provided by the owners of a given enterprise should be valued at the cost of obtaining these services from an alternative source in a market transaction.

To summarize the findings of economic analysis, it is useful to estimate economic indices, which reveal the potential and viability of agricultural investments. Generally accepted indices also provide a basis for comparison between alternative investment plans.

The basic financial indices appropriate for economic analysis of crop sustainability are the following (see, for example, Lumby and Jones, 2001; Götze et al., 2007):

1. Return on total assets (ROTA): This ratio shows how efficiently assets are generating earnings (before interest and tax) as a percentage of total assets. It shows the profitability achieved by each euro of the assets required by the project.
2. Payback period: This is one of the simplest and most widely used investment appraisal indices. It measures the number of years needed for net project inflows to pay back the initial investment. In the case of multiannual agricultural projects, *initial investment* includes the usual land, machinery and equipment, buildings and constructions, and the expense of purchasing and installing the plantation. This simple type of index does not require discounting of future cash flows. It shows not only the speed of capital recovery, but also the degree of risk, since the shorter the payback period, the lower the risk.

3. Net present value (NPV): This is the present value of the stream of net cash flows (inflows minus outflows) during the economic life of the plantation. This financial metric is a measure of the economic attractiveness of projects. Positive NPVs indicate projects capable of generating entrepreneurial surplus after having paid all project costs and expenses, including the initial investment outlay.

   The mathematical formula for the calculation of NPV is presented in Eq. (8.2):

$$\mathrm{NPV} = \sum_{t=0}^{n} \left[CF_t \times (1+d)^{-t} \right] \tag{8.2}$$

   where CF_t is the net cash flow of year t (inflows minus outflows), CF_0 is the net cash flow of year 0, usually the initial investment outflow (negative), CF_n is the net cash flow of year n, including possible land restoration costs or positive terminal value of the plantation, n is the number of years of the economic life of the plantation, and d is the discount rate.

4. Internal rate of return (IRR): This is the discount rate (d) for which NPV = 0. The higher the discount rate, the lower is the NPV. Therefore the IRR indicates the maximum rate of return (ceiling) that the project can achieve, or the maximum interest charge of invested capital beyond which the project is not financially rewarding.

   Investment projects are being financed if their IRRs are sufficiently higher than the cost of borrowing and cover the risk of investment.

8.2.4 Socioeconomic Analysis

The socioeconomic aspects are interlinked with the economic analysis and assess the socioeconomic impacts focusing on both quantitative (jobs, direct, indirect, and induced) and qualitative (contribution to rural economy, local embedding, and proximity to markets) parameters.

Usually, methodological approaches combine qualitative and quantitative assessment and evaluate respective impacts in two categories, i.e., employment effects and social sustainability (Table 8.1).

Table 8.1 Impact categories, criteria, and indicators for the socioeconomic impact analysis

	Category	Criterion	Indicator
Quantitative parameters	Employment effects	Jobs (creation/ maintenance)	Direct job equivalents for the value chain Indirect job equivalents for the value chain Net additional induced jobs
Qualitative parameters	Social sustainability issues	Contribution to rural economy	Qualitative (high, moderate, low)
		Local embedding	Qualitative (high, moderate, low)
		Proximity to markets	Qualitative (high, moderate, low)

Employment created can be measured as *direct* (those employed by the project itself), *indirect* (those employed in supplying the inputs to the project), and *induced* (those employed to provide goods and services to meet consumption demands of additional directly and indirectly employed workers).

Employment effects calculate job creation from the full value chain. Net job creation as a result of the deployment of biomass should be regarded over the *full value chain*. This can be expressed in number of full-time jobs per value chain, per ton of biomass input, or per gigajoule of end products (Pelkmans et al., 2014). When considering perennial crops production and use, the jobs calculated are net created jobs (created jobs minus lost jobs due to replaced previous uses of the land).

The criterion can be further expressed by the following indicators:

Direct jobs: The following value chain steps require employment that could be included in the measurement of direct jobs created:

- Bioenergy feedstock production;
- Biomass transportation;
- Biomass conversion and processing;
- Manufacturing of equipment;
- Distribution and sales;
- Installation of conversion plants and other equipment;
- Operation and maintenance of conversion plants and other equipment;
- Major research and development related to any of the foregoing activities.

Indirect jobs: Apart from the direct jobs created across the value chain there are indirect jobs that are created by other businesses that come into existence and/or support the development, economic viability, and sustainability of the actual value chains. For example, manufacturing and construction jobs for the equipment and plants count as indirect and do not last beyond the purchase of equipment or the start of plant operation. Consultants are generally independent contractors and do not count.

Net additional induced jobs: This indicator refers to the jobs that support demands of additional directly and indirectly employed workers to provide goods and services to meet consumption.

Social sustainability evaluates the impacts of the value chain to society and the rural economy. The impact category usually includes:

- Risk of child labor: Child labor is defined by the International Labour Organization (ILO) as employment of children in any work that deprives children of their childhood, interferes with their ability to attend regular school, and that is mentally, physically, socially, or morally dangerous and harmful. Not all work by children is considered child labor in this sense.
- Risk of forced labor: All work or service that is exacted from any person under the menace of any penalty and for which the said person has not offered himself voluntarily (ILO, Forced Labour Convention, 1930).
- Risk of country not passing laws to protect indigenous rights: Indigenous rights are those rights that exist in recognition of the specific needs and conditions of indigenous peoples. This includes particularly the preservation of their land, language, religion, and other elements of cultural heritage that are a part of their existence as a people.
- Risk of not having access to improved sanitation: Improved sanitation is defined as sanitation in a facility that hygienically separates human excreta from human contact.

- Contribution to rural economy: Employment is a major issue in rural economies. Certain value chains may induce more regional job creation, stimulating the rural economy, while other value chains may be more directed to large-scale industry, often in the hands of international players/multinationals.
- Local embedding: The capacity of the local economy to develop and operate a full value chain or part of it (e.g., in the OPTIMA case the production of perennial crops).
- Proximity to markets: The indicator expresses the difference between a more local approach with low distances (feedstock converted and consumed locally) on the one side, and on the other side a more international/industrial approach where the feedstock is transported to large industrial sites or to harbor areas to be exported.

The first four criteria are mostly related to biomass produced outside Europe and imports. They often concern life and working conditions in poor countries with low safety standards, and even if companies are not directly involved, their supply chains—perhaps unrecognized by themselves—may well make them responsible for obvious mistakes (Mueller-Lindenlauf et al., 2014). High-risk potentials for forced labor in Europe are topical according to a most recent report commissioned by the UK-based Joseph Rowntree Foundation.

According to Feldt and Kerkow (2013), governments should strive to establish a coherence of the raw material strategy with human rights obligations, risk assessment for human rights violations for trade agreements of the European Union with third countries, making support programs for projects in foreign countries dependent on due diligence for human rights, establishing raw materials partnerships with foreign countries including assessment of consequences for human rights, and supporting governments in foreign countries to enact issues such as right of codetermination and in particular the right for free, early, and informed agreement of indigenous people to projects concerning their own environment and living.

The same source recommends to enterprises, among others, that they integrate human rights principles in their own policies at the highest management level, claiming for human rights standards in supply contracts, establishing independent auditing with a focus on human rights risk assessment, developing certification that addresses all relevant human rights standards, establishing a material data bank including all relevant information for use in suppliers' evaluation and requirements for tender formulations, and establishing a reporting system on one's own practice and efforts to gain influence for the supply chain with regard to human rights.

8.2.5 Integrated Sustainability Assessment

Several approaches for comprehensive sustainability assessments of products or processes along their whole life cycles have been suggested in the last few years (Finkbeiner et al., 2010; Heijungs et al., 2010; Klöpffer, 2008). However, most methodologies for sustainability assessment were developed for assessing existing systems. This is not sufficient for ex-ante decision support because an extrapolation from the past to the future is not necessarily valid. Instead, potential future systems (i.e., decision options) have to be compared to each other in the form of scenarios. Keller et al. (2015) have therefore developed a flexible, modular, scenario-based, and practicable methodology, termed "integrated life cycle sustainability assessment" (ILCSA), which can overcome the limitations of other approaches and yield valuable comprehensive decision support with manageable effort.

The assessment procedure can be divided into three steps:

1. Definitions and settings
   Common definitions and settings are specified that apply to all parallel assessments of the various sustainability aspects to ensure the compatibility of results. This includes goal and scope questions, descriptions of assessed scenarios and further definitions and settings. Importantly, scenarios depict potential future implementations of mature technology, i.e., the alternatives relevant to strategic decision-making, not the current status of development.
2. Parallel assessment of various sustainability aspects
   The assessments include impacts on environment, economy, and society, which are commonly referred to as the three pillars of sustainability. The implementation of scenarios that are found to be sustainable in a sustainability assessment may, however, still cause unexpected and sometimes undesirable consequences if they cannot be implemented in the intended form or if operations stop after a short time. To increase the value for decision support, the scenarios are additionally assessed for several barriers that could hinder their implementation in the intended form, e.g., technological aspects, biomass potentials, and a strengths, weaknesses, opportunities, and threats analysis.
3. Result integration
   A dedicated procedure has been developed to join all assessment results into an overall picture and derive conclusions and recommendations for decision support.

   For a detailed description of the ILCSA methodology and its advantages over LCA or life cycle sustainability assessment (LCSA) please refer to Keller et al. (2015).

8.3 Environmental Aspects of Perennial Crops Production and Use

8.3.1 Global and Supraregional Impacts

Environmental performance of perennial crops is usually beneficial once it contributes to the reduction of greenhouse gases and energy savings, as it has been reported by many studies (e.g., Cipriano and Fernando, 2012; Daystar et al., 2015; Fazio and Barbanti, 2014; Nguyen and Hermansen, 2015; Parajuli et al., 2015; Shemfe et al., 2016; van Dam et al., 2009). The crop yield, the amount of inputs in the agricultural phase, such as fertilizers, pesticides, and irrigation, the feedstock processing requirements, the energy conversion processes, and the types of coproducts affect the environmental performance of the biomass-based systems (Biewinga and van der Bijl, 1996).

Although biomass-based systems require nonrenewable energy for the cultivation, transport, and conversion to bioenergy, the energy balance associated with the whole life cycle, measured by the ratio of nonrenewable energy input/energy output, is usually lower than 1, meaning that it consumes less nonrenewable energy than the energy it provides. Cherubini et al. (2009) reported the electricity and heat generation from combustion of several perennial crops. According to these authors the use of miscanthus, switchgrass, and giant reed for electricity and cogeneration saves 105–315 GJ ha^{-1} yr^{-1}, lower than if used for heating generation only (150–515 GJ ha^{-1} yr^{-1}), but higher than second-generation bioethanol (25–95 GJ ha^{-1} yr^{-1}). The same study reports that those lignocellulosic crops give greater energy savings per hectare than wood chips and wood pellets or kenaf, hemp, and cardoon, by means of the same energy-generating technologies, and similar to those reported for sweet and fiber sorghum.

Biomass use for energy or materials is considered a "carbon saver" over its life cycle as carbon has been captured from the atmosphere and has been photosynthetically transformed into biomatter using solar radiation, water, and external inputs (e.g., fertilizer, pesticides, machinery, fuel for farm vehicles, etc.). However, a portion of CO_2 is emitted during the cycle of biomass production and use: external fossil fuel inputs are required to cultivate and harvest the feedstocks, in transport and in processing and handling the biomass. Other gases can also contribute to the greenhouse effect such as N_2O (attributed to the nitrification and denitrification processes occurring during crop cultivation) and CH_4 (considered relevant when soils under native conditions represent a large storage of carbon), which can be quantified in terms of CO_2 equivalents. Use of perennial grasses for bioenergy can save 2–33 $MgCO_2$-eq ha^{-1} yr^{-1}, when used for electricity and cogeneration, 13–58 $MgCO_2$-eq ha^{-1} yr^{-1}, when used for heating generation, but merely 2–7 $MgCO_2$-eq ha^{-1} yr^{-1}, when used to produce bioethanol (Cherubini et al., 2009), similar to the annual crops sweet and fiber sorghum, and higher than what was stated for wood chips and wood pellets or kenaf, hemp, and cardoon.

Regarding other environmental impact categories, e.g., acidification and eutrophication, production and use of perennial crops show disadvantages or inconclusive results (Murphy et al., 2013; Rettenmaier et al., 2010; Zucaro et al., 2016).

The acidification potential (the ability to form H^+ ions) is measured in SO_2 equivalents, and the relevant acidifying substances associated with production and use of perennial crops are NH_3, SO_x, and NO_x. These substances when released to air, land, or water may alter the pH, which in turn affects the solubility and hence availability of organic and inorganic substances contained therein, affecting processes, such as heavy metals and nutrients uptake by the plants. Concerning perennial crops cultivation and use, acidifying emissions can take place in the production of nitrogen fertilizers (source of NO_x and NH_3 emissions), and by NO_x and SO_2 emissions released during the use of the biomass material. However, NO_x emissions contribute to a higher proportion of the acidification potential of cultivation and use of perennial crops than SO_2 emissions, because nitrogen is a major component of biomass as opposed to sulfur (Oliveira et al., 2001; Vassilev et al., 2010). Moreover, the less intensive management associated with perennials reduces the acidifying emissions associated with its cultivation by comparison with annual crops (Fernando et al., 2010a, 2011). The acidification potential through the substitution of fossil sources with biomass depends not only on the crop, but also on the conversion technology, the method of biomass cultivation, and the fossil source that is substituted (Kaltschmitt et al., 1996). Rettenmaier et al. (2010), in their work, showed that the production and use of perennial crops presented neutral or negative impacts regarding the acidifying emissions, depending on the conversion technology. The production of diesel through gasification followed by the Fischer–Tropsch process, the production of heat and power, and the production of power showed egalitarian results to the fossil reference system. However, hydrolysis and fermentation to produce second-generation ethanol and direct combustion to produce heat showed environmental disadvantages compared to conventional counterparts. Zucaro et al. (2016) when evaluating the production of second-generation bioethanol from *A. donax* L. also reported an increased acidification potential in comparison with gasoline.

Perennial crops production and use contribute also to eutrophication (enrichment of a water body with nutrients) (Rettenmaier et al., 2010; Zucaro et al., 2016). Yet, concerning this impact category, it has been suggested that nitrogen and phosphorous leaching are easily trapped and filtered by the underground root system of perennials (Barbosa et al., 2015b, 2016; Costa et al., 2016; Fernando et al., 2016) linking perennials to areas vulnerable to nitrate water pollution, wastewater treatment, landfill leachates, and as buffer strips to traditional farming systems (Fernando et al., 2012). Moreover, perennial crops require lower fertilizer inputs than annuals, with positive economic and environmental gains (Zegada-Lizarazu et al., 2010). Because some of the herbaceous crops may use organic nitrogen from nitrogen-fixing bacteria, free or associated to root systems (e.g., giant reed and switchgrass), nutrients are recycled by the rhizome system, being translocated from aerial to underground parts at the end of the growing season, and being demobilized in spring for regrowth because their extensive root system can easily immobilize nutrients, thus increasing nutrient use efficiency (Fernando et al., 2012; Picco, 2010).

Summer smog is formed when radiation from the sun causes ozone to build up in the troposphere, by combining nitrogen oxides and volatile organic compounds, presenting adverse effects on human health, agricultural crops, natural vegetation, and materials. Concerning summer smog, the contribution of perennial crops production and use is the same or even advantageous (hydrolysis and fermentation to produce second-generation ethanol) compared to the fossil reference system (Rettenmaier et al., 2010; Zucaro et al., 2016). Antagonistically, herbaceous crops use contributes to human toxicity (particulate air pollution) (Zucaro et al., 2016), except when used to produce diesel, through gasification followed by the Fischer–Tropsch process, or combusted to produce heat and power, where the results are similar to the fossil reference system (Rettenmaier et al., 2010). Ambiguous results can be found regarding the effects on the ozone layer (which prevents the most harmful UVB wavelengths in the stratosphere). The ozone depletion potential associated with the production of second-generation ethanol from giant reed was considered beneficial by Zucaro et al. (2016) in comparison with gasoline, and in contrast with the negative impact results reported by Rettenmaier et al. (2010) associated with the production and use of herbaceous crops in comparison with the fossil reference system.

8.3.2 Local Impacts

There are a few studies that cover local and site-specific environmental impacts associated with the production and use of perennial crops. The few existing studies focus usually in only one category, e.g., biodiversity or soil quality, and are limited to the cultivation phase. Also the majority of the existing studies usually addresses only one crop and compares it with idle land or with another crop.

Fernando et al. (2010b), in their study, applied to the cultivation of 15 potential energy crops in Europe, addressed some local and site-specific categories, namely, impacts on water resources and soil, landscape, and biodiversity. The findings suggest that lignocellulosic crops exhibit lower erodibility potential, higher biological and landscape diversity, and positive impacts regarding soil organic matter and soil structure, compared to annual crops, due to greater interception of rainfall, more surface cover, continuous permanence in the soil, reduced soil tillage and use of agrochemicals, high above- and belowground biomass, high inputs of residues, deep and dense root systems, and vigorous root development. Additionally, the less intensive soil amendment in perennial systems results in reduced pH variations from the native status of the soil and, with the exception of giant reed, shows N and K deficits; the soil's nutrient status also reduced disturbance. With these features, cultivation of these species provides benefits to soil fertility, such as improving its structure and porosity, increasing the field capacity, and extending storage capacity and availability of nutrients. Furthermore, perennial crops have lower impact on water resources than annuals: perennials present high lignin and cellulose contents, allowing the plants to stand upright at low water contents (Lewandowski et al., 2003); they show a high water use efficiency due to their deep and well-developed root system (Cosentino et al., 2007, 2014; Monti and Zatta, 2009); and the high soil coverage minimizes surface runoff (Fernando et al., 2010b). Yet the deep root systems may reduce aquifer refilling, causing a negative impact in the ecosystem (Fernando et al., 2012).

The lower requirement of pesticide inputs, by comparison with annual crops, represents also a supplementary environmental advantage of perennial crops. This is because perennials take advantage of the use of herbicides only during the planting phase of the crop, while annual crops require year-round applications, and some energy crops, e.g., miscanthus and giant reed, present no major illnesses requiring plant protection measures (Fernando et al., 2010a, 2012). Beneficial effects are the decreasing shares of chemicals ending up in soil, water, and air, causing damage to flora and fauna and affecting human health (Fernando et al., 2010a, 2011).

The increment of organic matter content in the soil contributes to soil carbon storage (carbon sequestration) and reduction of CO_2 in the atmosphere. Perennials (e.g., switchgrass, miscanthus, and giant reed) have a good aptitude to store carbon in the soil, mainly due to their large and deep root development, since a large parcel of the organic carbon synthesized during photosynthesis remains in the ground in the postharvest. According to Fernando (2013), carbon sequestration by the miscanthus root and rhizome system is considerable, representing c. 12.5–13.5 Mg ha^{-1} over the lifetime of the crop, and recycled carbon to soil from litter represents c. 3.1–3.9 Mg ha^{-1} yr^{-1}. Monti and Zegada-Lizarazu (2016) reported soil organic carbon (SOC) gains under giant reed fields of 0.6–1.0 Mg $ha^{-1}yr^{-1}$, with an accumulation in the topsoil of 12 Mg ha^{-1} over 16 years. In the model simulation of cumulative carbon sequestration by switchgrass in the Mediterranean area, Nocentini et al. (2015) quantified an annual SOC accumulation of 0.02–0.62 Mg ha^{-1} and an accumulation of 3.5–4.2 Mg ha^{-1} over 15 years. Moreover, Nocentini et al. (2015) also stated that if switchgrass were cultivated in arable land, the consequent indirect land use change effects were low when compared to the environmental benefits of the stored SOC. However, this soil–rhizome accumulation can become prejudicial if land use changes, due to the release of the stored carbon.

Perennial crop characteristics (rapid growth, high yields, deep and extensive root systems) explain the tolerance capacity of these plants to marginal and contaminated soils (Alexopoulou et al., 2015; Bosco et al., 2016; Fernando et al., 2014). This capacity offers the possibility of associating soil decontamination and restoration with the production of biomass for bioenergy and biomaterials with additional revenue (Fernando et al., 2016). Also use of marginal/contaminated soils contributes to reduce the land versus food dilemma (Lewandowski, 2015) and the minimum direct and indirect negative effects due to land use change (Fritsche et al., 2010). The remediation capacity of perennial grasses has been demonstrated by several studies, such as those with miscanthus (e.g., Boléo et al., 2015; Barbosa et al., 2015a; Nsanganwimana et al., 2014; Pidlisnyuk et al., 2014), giant reed (e.g., Barbosa et al., 2015a; Fernando et al., 2016; Liu et al., 2017; Sidella et al., 2016), or switchgrass (Arora et al., 2016). Yet the adequacy between the crop and the respective marginal/contaminated soil to avoid potential environmental and socioeconomic impacts should be taken into account (Boléo et al., 2013). In fact, sustainability of energy crop production in marginal/contaminated soils depends on crop yields and crop's ability to restore value to the land. Productivity loss in marginal/contaminated soils diminishes the energy and greenhouse savings but the presence of vegetation may contribute to improve the quality of soil and waters and biological and landscape diversity (Fernando et al., 2014).

The characteristics of perennial crops also allow the association of their cultivation with the use of wastewaters in irrigation (Barbosa et al., 2015b). The application of treated wastewater to fields of perennials may contribute to mitigating the scarcity of water resources and reduce the need for fertilizers, with global positive environmental outcomes (Fernando et al., 2015a). Irrigation with wastewaters may provide readily available adequate amounts of N, P, and K and also sufficient quantities of organic matter that improve the soil structure and other soil properties related to availability of water and nutrients. According to Khan et al. (2009), the use of treated wastewater may increase total carbon, total nitrogen concentration, and mineral content along with microbial activity in soil that helps nutrient availability to plants. Moreover, with extensive radicular systems, perennial crops have the potential to simultaneously deliver high yields and promote water quality improvement, protecting freshwater resources, as observed in the work of Costa et al. (2013) with giant reed, and in the works of Bandarra et al. (2013) and Lino et al. (2014) with miscanthus. In the cited works, perennial–soil systems accomplished the removal (>90%) of large amounts of contaminants from the wastewaters rich in heavy metals. Yet the pros and cons of combining wastewater irrigation with perennial grass production should be adequately weighed, so that opportunities to produce sustainable biomass can be effective. Indeed, the presence of harmful substances in wastewaters can also be detrimental to biomass growth and quality, and, if not accurately trapped by the standing biomass, contaminants can accumulate in the soil or be leached to the ground and surface waters, causing a threat to the ecosystems.

8.4 Economic and Socioeconomic Aspects of Perennial Crops Production and Use

8.4.1 Financial and Economic Aspects of Perennial Crops Production and Use

Financial analysis is concerned with the measurement of performance against set targets on every aspect of a project. It identifies the efficiency of use of resources and provides suggestions for improving overall performance. It also measures the effectiveness of management in mobilizing the factors of production for the achievement of financial goals and supports the search for improved approaches. Finally, it is a useful tool for determining areas of possible economic improvement, assisting management in their efforts toward the overall improvement of performance.

Financial analysis of biomass production comprises three easily identifiable steps. The first is farm income analysis, based on balance sheet and profit and loss accounts. This is based on an opening balance sheet and farm budgets projecting income and expenses for the following years. The second step consists of the estimation of future balance sheets based on farm sales and income forecasts and on assumptions regarding the timing of receipts and payments (Walsh, 2010). This step identifies project-related future cash flows, which can be achieved either directly (based on timed receipts from sales, etc. minus payments for purchases and expenses) or indirectly (based on net earnings before depreciation plus changes in working capital) (Walsh, 2010). The third step is farm investment analysis. This utilizes cash flows from step 2 to estimate the attractiveness of the project by comparing future net inflows with initial investment outlay (Bierman and Smidt, 2007).

Financial sustainability of perennial crops identifies thresholds of financial viability indicators in comparison to alternative courses of action for the supply of final products that may be produced from biochains based on such industrial crops.

From the viewpoint of the producer of bioproducts (farmer, industry, supplier, investor, etc.), sufficient return to invested effort or capital must be secured within affordable risk levels, reasonably fast and with adequate prospects for maintaining the activity in the future (sustainability). With regard to the production of bioenergy, the European Commission has set high targets for carbon reduction and renewable energy contribution to the EU energy sector. The targets for 2030 are much higher than the 2020 goals and this signals a consequent expansion of the cultivation of perennial energy crops.

The potential value of the final products of perennial crops is measured by the difference between the selling price and the estimated annual equivalent life cycle cost, which is a measure of profitability. We assume no intermediate sales profit among the various actors along the biochains. Any positive overall profit margin is distributed among all contributors (farming, transport, warehousing, conversion, marketing, etc.) according to relative contribution and market forces.

Perennial grass cultivation and energy generation have been economically analyzed for several climatic and political regions in Europe (Alexopoulou, 2010). In the study it was considered that these crops are either burned for the production of heat and electricity or pelletized for sale in the domestic and industrial sector. Costs and revenues of plants were measured against the opportunity cost of land that they occupy and growers' profitability was examined in an attempt to maximize it. Results showed that perennials may be better planted in surplus land, although their financial best was achieved when cultivated on good agricultural land in spite of its increased land rent. In all cases it was revealed that the increased level of inputs is compensated for by the higher output sales due to higher yields achieved in the fertile soil.

Khanna et al. (2008) examined the costs of producing switchgrass and miscanthus in Illinois (USA) for cofiring with coal to generate electricity. Results indicated that the costs of using perennials for bioenergy was considerably higher than the costs of coal-based energy, and was not economically attractive. Yet the authors indicated the need for policies that would provide incentives for producing and using bioenergy crops based on their environmental benefits in addition to their energy content.

8.4.1.1 Cultivation of Industrial Crops in Marginal Land

The European Commission have repeatedly declared the intention to avoid the cultivation of nonfood, and especially energy crops in fertile agricultural land, to avoid the consequential effects on food supply and prices (EC/JRC, 2013; European Commission, 2009; EEC, 1975). Direct or indirect land use changes, mainly caused by renewable energy initiatives, have frequently affected the food market in many areas (European Commission, 2009). Therefore it is not unreasonable to encourage the cultivation of such perennial crops on various types of marginal land.

Land rent varies significantly from region to region. The rent of marginal land is not set equal to zero, unless the land has no potential for production and income. For marginal land, a 30%–60% discount off the rental of fertile agricultural land was identified, depending upon the degree of marginality and other factors. However, as this is very much site and case specific, it is best to estimate the rent of marginal land at its opportunity cost, i.e., the profit forgone because of the change of land use (Lewis and Kelly, 2014; Kang et al., 2013).

Irrigation is another major cost item, especially for cultivation in marginal lands, because they are usually water-stressed areas and the water may have to be transported from too far. Considerable amounts of energy and subsequent expense may therefore be necessary for the irrigation of marginal lands. It has been observed though that cultivation in marginal lands with minimal irrigation and other inputs is not usually an optimal choice, because of the disproportionately low agricultural yields.

Subsidies that may exist along the bioproducts chain should not be included in basic calculations. Such financial incentives are best considered *after* a basic evaluation of the attractiveness of the project "before subsidies" to show their effect separately.

8.4.1.2 Annual Equivalent Economic Performance

Life cycle performance estimation is important for perennial crops. Inspecting costs and benefits of only one particular year is of little use because some operations are not repeated regularly and uniformly year after year and therefore annual costs may differ through time during the plantation life. Furthermore, the productivity of the plantation may also differ from year to year. For example, perennial energy crops are expensive to establish and have lower annual costs for the rest of their productive life, while they also give lower yields at the early years and have increased productivity later.

Consequently, costs and returns estimation could be reported either for "every" individual year or for a "typical" year when the crop is mature. The first approach leads to results that are less comprehensive and are difficult to use for comparison with other investment proposals. The second, usually reflecting conditions "at maturity," disregards the inferior economic performance in periods of lower yields or increased input requirements such as the early years.

Economics seeks to estimate a net benefit, representative of the whole economic life of perennial plantations, which allows direct comparisons among different crops with different lifetimes. This life cycle economic approach incorporates the cost of initial investment and all lifetime income and expenses. The life cycle economic performance of a crop is calculated as an *annual equivalent* value (directly corresponding to the NPV of the project) incorporating all relevant lifetime cash flows by adopting discounting cash flow (DCF) methods (Kruschwitz and Loeffler, 2005). To calculate the annual equivalent value of a project, the present value of all net cash flows over the useful life of the plantation is transformed into an equivalent annuity extended over the same time period.

Given a discount rate (d) and the plantation useful life (n),

$$\text{Annual Equivalent Value }(R) = N\text{PV} \times \frac{d}{1-(1+d)^{-n}} \tag{8.3}$$

where NPV is given by Eq. (8.2) and year zero is the investment year.

8.4.2 Socioeconomic Aspects

There are three main categories of socioeconomic aspects of perennial crop production and use that are analyzed in respective research worldwide: macroeconomic, supply, and demand. These three categories are outlined next.

Increased use of perennial crops could provide farmers with opportunities for alternative revenue streams as well as commercial opportunities for related industries that can exploit the feedstock as raw material. Furthermore, the use of indigenous raw materials can help retain employment as well as local welfare by recirculating money within the local/regional economy. The key macroeconomic impacts as reported in recent literature are:

- Rural diversification;
- Regional growth;
- Reduced regional trade balance;
- Export potential.

Supply-side impacts result from improvements in the competitive position of the region, including its attractiveness to inward investment (Madlener and Myles, 2000). These effects are regionally/locally specific and relate to changes and improvements in regional productivity, enhanced competitiveness, as well as any investment in resources to accommodate any inward migration that may result from the development. The key supply impacts as reported in recent literature (Domac et al., 2005) are:

- Increased productivity;
- Enhanced competitiveness;
- Labor and population mobility (induced effects);
- Improved infrastructure.

Demand-side impacts are primarily quoted in terms of employment and regional income. They can be categorized accordingly into direct, indirect induced, and displacement effects. The key demand effects as reported in recent literature (Domac et al., 2005) are:

- Employment;
- Income and wealth creation;
- Export potential;
- Support of complementary industries;
- Rural diversification.

8.5 Case Study: Optima Project

8.5.1 Investigated Perennial Crops and Value Chains

The OPTIMA project focused on the cultivation of the perennial crops giant reed (*A. donax* L.), miscanthus (*Miscanthus* × *giganteus*), and switchgrass (*Panicum virgatum* L.) in marginal soils in the Mediterranean region. The life cycle of the systems includes cultivation, harvest and pretreatment, conditioning and logistics, conversion, use phase, and end of life. Life cycle phase "cultivation" can be subdivided into the following processes: field preparation, seeding/planting, maintenance including weed control, the application of fertilizer and irrigation, harvest, and clearing after a plantation's lifetime. Several parameters are equal for each of the plants, including the plantations' lifetime of 15 years. However, the crops' plants differ from each other with respect to the magnitude of inputs and outputs associated with the cultivation phase (Table 8.2).

Different value chains were analyzed within the OPTIMA project: (1) domestic heat; (2) combined heat and power (CHP), small and large scale; (3) upgraded pyrolysis oil; (4) biochar; (5) second-generation ethanol; and (6) 1,3-propanediol. These value chains form a representative mix of scales and applications that can both be sourced by the three perennial crops but also be suitable for conditions in Mediterranean countries. More details can be found in Fernando et al. (2015b), Schmidt et al. (2015), and the OPTIMA project webpage (www.optimafp7.eu).

8.5.2 Life Cycle Assessment

A screening LCA for the cultivation and use of three selected perennial grasses, miscanthus, giant reed, and switchgrass, was conducted as part of the sustainability assessment of the OPTIMA project. As a basic set of scenarios, 21 combinations

Table 8.2 **Input and output data of the cultivation of perennial crops on marginal land**

Parameter	Unit	Giant reed	Miscanthus	Switchgrass
Moisture at removal from field	% fresh matter	55	20	15
Biomass removal from field (average over plantation's lifetime)	t dry matter/(ha year)	17.5	14	8.75
Irrigation	m^3/(ha year)	6000	6000	4000
N fertilization	kg N/(ha year)	111	38	63
P fertilization	kg P_2O_5/(ha year)	60	16	16
K fertilization	kg K_2O/(ha year)	385	102	22

of three crops and seven use options have been analyzed for their impacts on seven environmental indicators in a screening LCA (see Schmidt et al., 2015 for LCA methodology).

8.5.2.1 Exemplary Results for Individual Environmental Impact Categories

Comparing bioenergy paths to conventional ways of providing equivalent products requires analyzing many individual life cycle steps. This section explains for one specific scenario (miscanthus used for small CHP production) and two environmental impact categories (climate change and acidification) how these life cycle steps contribute to the overall result (Fig. 8.2).

Fig. 8.2 depicts the impacts of individual life cycle stages (bars with gray-colored sections) and how they contribute to the overall results. There are expenditures associated with each bioenergy life cycle, which are depicted as positive (additional) emissions. The avoided emissions from the replaced processes are credited to the bioenergy scenario and are thus depicted as negative emissions in Fig. 8.2.

From Fig. 8.2, one can see that bioenergy schemes have important impacts not only on climate change but also on other environmental aspects, which have to be taken into account in the same way. Furthermore, it becomes clear that the use of miscanthus for heat and power production can cause both advantages and disadvantages at the same time in different environmental impact categories. In such cases, the question arises how to compare the different environmental impacts. Weighting the impacts on the basis of personal value choices, beyond scientific arguments, is not done in this study. To compare the magnitude—not the severity—of different impacts in a scientifically sound way, it is possible to normalize the results using inhabitant equivalents (IEs). In this case, the impacts caused by a certain process, e.g., per hectare per year, are compared (normalized) to the average annual impact that is caused by an inhabitant of the reference region. For normalization factors please see Schmidt et al. (2015).

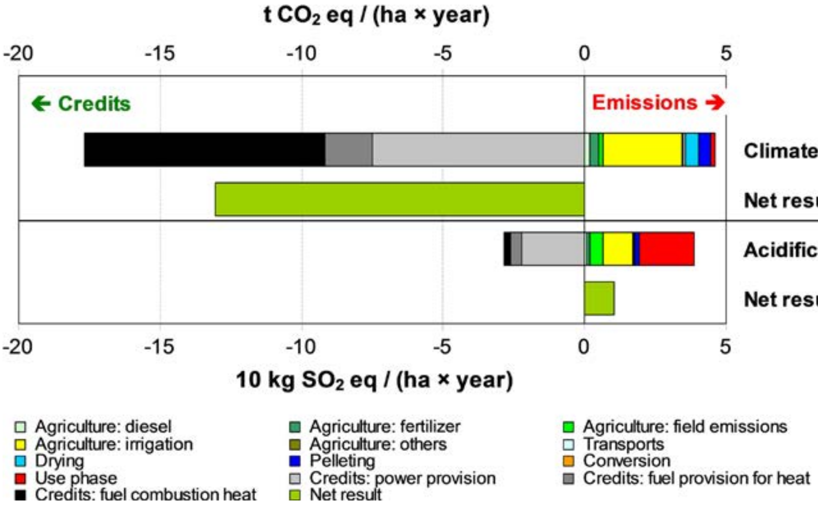


Figure 8.2 Contributions of individual life cycle steps to the overall net result of the scenario "*Miscanthus*→Small CHP" compared to the fossil equivalent in the environmental impact categories climate change and acidification.

8.5.2.2 Normalization of Results

In Fig. 8.3, the environmental advantages and disadvantages are related to the environmental situation in the EU28. The reference information is the annual average resource demand and the average emissions of various substances per capita in Europe, the so-called IE. The environmental impacts per unit (e.g., x t CO_2 equiv. $10\,ha^{-1}\,yr^{-1}$) of the life cycle are divided by the annual average impact per inhabitant, thus yielding a dimensionless value per unit (e.g., y IE $10\,ha^{-1}\,yr^{-1}$).

8.5.2.3 Comparison of Perennial Grasses and Use Options

To give a general impression of the impact of the agricultural processes with respect to the conversion and usage processes on climate change, Fig. 8.4 gives an overview in a 3D diagram. It shows that the differences in the results of the seven usage options are larger than the differences between the biomass types.

With respect to the ranking of crops and use options, it has to be underlined that some scenario settings such as drying and pelleting of all biomass significantly influence the results. Depending on the case-specific circumstances, logistics chains could be designed differently.

While Fig. 8.4 shows a remarkable result matrix of the standard scenarios, but only in one environmental impact and not for the sensitivity analyses, Fig. 8.5 provides more details in different aspects of interrelations between the results. It gives an overview of the basic scenarios in the OPTIMA project: all perennials and conversion/usage options investigated are displayed. The figure shows that the choices of both conversion/use option and the perennial crops used substantially influence the results.

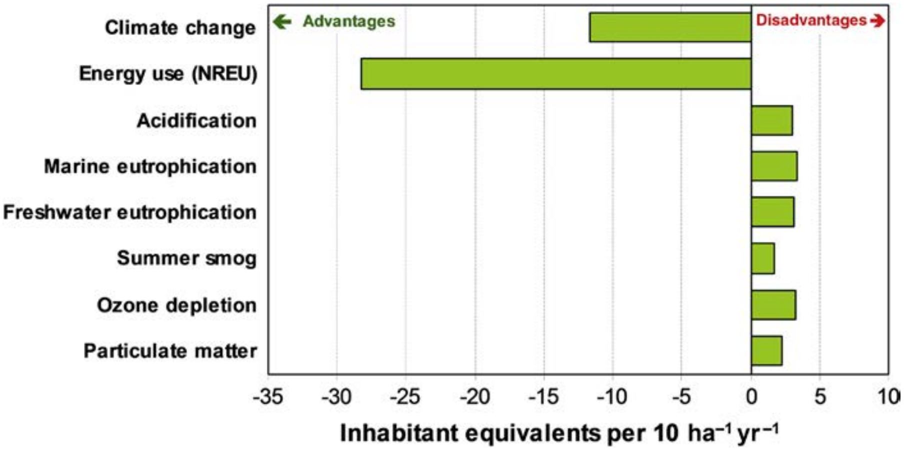


Figure 8.3 Overall net result of the scenario "*Miscanthus*→Small CHP" compared to fossil equivalent products in all environmental impact categories regarded in this project. *NREU*, Nonrenewable energy use.

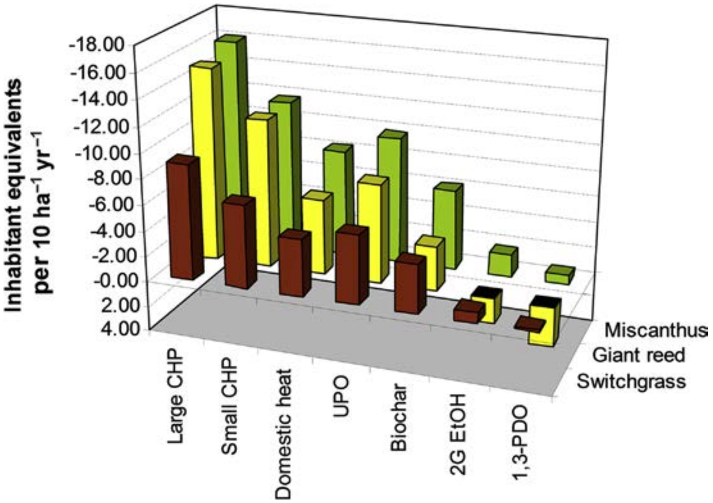


Figure 8.4 Overall greenhouse gas savings (*upward columns, negative numbers*) or extra emissions (*downward columns, positive numbers*) of all main scenarios with the biomass feedstock cultivated on marginal land used in the use option with standard conversion efficiency, each compared to its fossil equivalent product. *1,3-PDO*, 1,3-propanediol; *2G EtOH*, second-generation ethanol; *CHP*, combined heat and power; *UPO*, upgraded pyrolysis oil.

8.5.3 Environmental Impact Assessment

In the framework of the OPTIMA project, the environmental impacts related to the production and use of perennial grasses cultivated on marginal lands in the Mediterranean region, focusing on local impacts, were also assessed. Effects of producing these

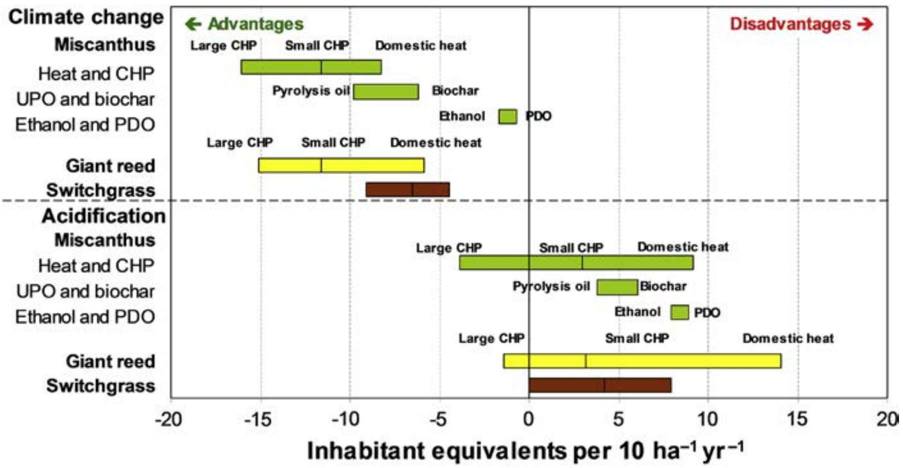


Figure 8.5 Life cycle assessment results for the basic scenarios: the different crops and conversion/use options. Conversion/use options are shown for standard conversion efficiency based on the cultivation of miscanthus in marginal land; agricultural options are shown for yield level in marginal land based on heat and power use options. *CHP*, combined heat and power; *PDO*, 1,3-propanediol; *UPO*, upgraded pyrolysis oil.

grasses on the biodiversity, landscape, soil quality, and erosion and use of water were evaluated and compared with the effects of nonrenewable fuels (Fernando et al., 2015b) and compared with idle land, when considering only the cultivation phase (Fernando et al., 2017). Fig. 8.6 shows the impact of the cultivation and use of the studied perennial grasses in marginal soils of the Mediterranean region.

The study showed that local environmental impacts are mainly influenced by biomass cultivation. Miscanthus is the best performing crop at the local level because of its low nutrient demand and high yield. Overall results suggest that perennial crops provide benefits regarding soil properties and erodibility. Less tillage and high biomass production support biological and landscape diversity. Impacts associated with water resources can be lowered by adopting water- and energy-saving techniques, a strategy particularly important in the case of giant reed, which showed the highest impact score to water use. Regarding the best performing use option, small CHP and domestic heat use options are considerably more beneficial than conversion to ethanol or 1,3-propanediol (Fig. 8.7).

8.5.4 Economic Analysis

Recent research within the framework of the EU project OPTIMA (optimafp7.eu) has revealed the financial possibilities of cultivation of perennial grasses in marginal lands of southern EU regions and their transformation into a number of final bioproducts as part of a wider sustainability evaluation.

Three of the most promising perennial crops for Mediterranean climates have been studied as raw materials for the manufacturing of a number of mainly bioenergy

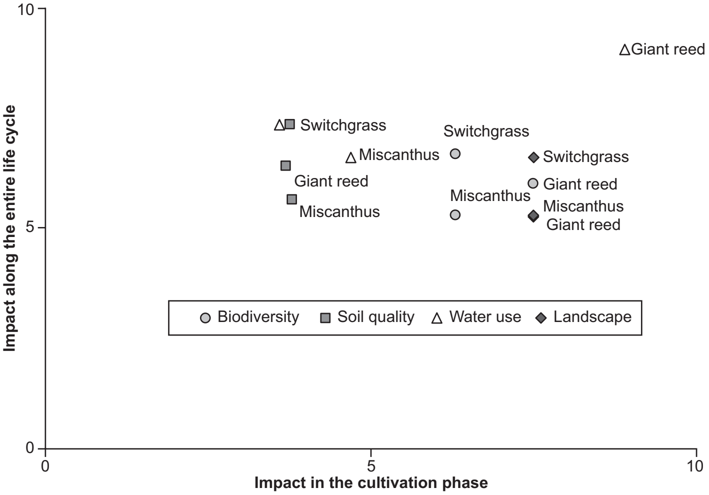


Figure 8.6 Normalized scores of the impact of cultivation and use of perennial grasses in marginal soils of the Mediterranean region. The *x* axis represents the impact of the crops on the cultivation phase when compared with idle land. The *y* axis represents the impact of the crops' cultivation and use for combined heat and power (CHP) production in a small CHP plant compared to the fossil equivalent. Indicator results were scaled from 0 (lower impact) to 10 (higher impact), with idle land and the fossil equivalent scoring 5 (in the middle of the range).

products: giant reed, *M.* × *giganteus*, and switchgrass. The study assumed different land marginality levels and compared the economic performance of the foregoing crops with cultivation of the same plants in typical (standard) fertile agricultural land. All crops need to be irrigated, at least at the early years, to achieve proper establishment and successful growth. Cultivation in marginal land increases the need for agronomic inputs such as irrigation, fertilizers, etc., according to the deficiencies of the particular marginal land. Therefore, from an economic point of view, it was examined whether the disadvantage of the increased need for inputs is counterbalanced by the low economic rent of marginal land.

The result of the economic evaluation of the three crops is summarized in Table 8.3. In marginal lands within high precipitation regions, irrigation can be minimal and less costly (M0). In drier marginal regions, irrigation is necessary for the survival of the plantation. Agronomic inputs in marginal land can be low (ML) or high (MH). In the standard fertile agricultural land the agronomic inputs are high (SH).

Giant reed is more productive and in spite of higher agronomic expenses, its cost per ton is lower (below the €65 ton^{-1} line in the high-input scenarios). On the other hand, miscanthus is about as costly per ton of output as switchgrass (around €65–80), although

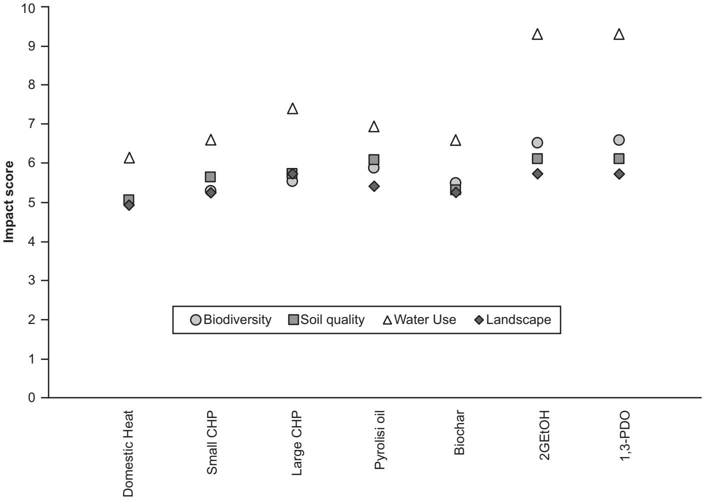


Figure 8.7 Comparison of the environmental impact assessment results of the different end use options of miscanthus on marginal land in the Mediterranean region. Different use options were compared with fossil equivalent. Indicator results were scaled from 0 (lower impact) to 10 (higher impact), with the fossil equivalent scoring 5 (in the middle of the range). *1,3-PDO*, 1,3-Propanediol; *2G EtOH*, second-generation ethanol; *CHP*, combined heat and power.

it achieves higher yields because it is more expensive to grow than switchgrass. It is worth observing that, due to lower marginal land yields, cultivation on low-quality land is in general more costly per ton of produced biomass, in spite of the lower opportunity cost (rent) of land and generally smaller amounts of agricultural inputs. Table 8.3 also shows the breakdown of costs by main operation category. It illustrates the relative significance of fertilization, irrigation, and harvesting, making up about 50% of the average annual cost of perennial grasses (all measured in annual equivalent terms).

A good number of biomass transformation processes based on the investigated crops were also evaluated by OPTIMA to compare the cost of whole bioproduct chains (from “cradle to grave”) against the value of competing products as detailed in Section 8.5.1.

Four major economic criteria for the evaluation of biomass-based value chains were calculated for each of the foregoing technological biochains and each of the three crops, namely: (1) ROTA, (2) IRR, (3) payback period, and (4) total assets turnover, as described earlier and found in many financial analysis books (e.g., Easton et al., 2015).

The detailed economic analysis of biomass value chains (summarized in Table 8.4) has shown that domestic heating with pellets from perennial grass biomass is successfully competing with oil heating (at 2014 oil prices), while CHP applications are

Table 8.3 Cost breakdown and productivity of marginal land cultivation of perennial grasses

In annual equivalent € ha^{-1}	**Giant reed**				**Miscanthus**				**Switchgrass**			
	M0	**ML**	**MH**	**SH**	**M0**	**ML**	**MH**	**SH**	**M0**	**ML**	**MH**	**SH**
Initial investment	198	198	204	204	198	198	204	204	57	57	61	62
Fertilization	113	113	159	159	113	113	159	159	113	113	159	159
Irrigation	11	178	253	253	11	178	253	253	11	126	178	178
Harvesting	198	243	276	300	142	198	243	276	107	139	198	249
Transport	134	177	220	306	96	120	144	192	72	96	120	144
Land rent, restoration, and overheads	131	133	136	240	151	157	164	281	141	147	157	270
Total cost, € ha^{-1} (delivered)	**786**	**1043**	**1247**	**1462**	**710**	**966**	**1166**	**1364**	**501**	**677**	**874**	**1063**
Yield, dry tons ha^{-1} (delivered)	12	15	20	25	10	12	16	20	7	9	12	16
Total cost € dry tons (delivered)	**65**	**70**	**62**	**58**	**71**	**80**	**73**	**68**	**72**	**75**	**73**	**66**

M0, marginal land, minimal irrigation; *MH*, marginal land, high input; *ML*, marginal land, low input; *SH*, standard agricultural land, high input. All calculations have been carried out with the help of package ABC (2017).

Table 8.4 Financial indices of perennial grass biomass transformation chains

Raw material		Domestic heat	Small CHP	Large CHP	Pyrolysis Oil	Biochar	Cellulosic ethanol
Giant reed	ROTA	14%	7%	17%	1%	3%	−24%
	IRR	12%	8%	13%	1%	2%	NA
	PBP	7.4	9.8	6.3	19	15	NA
	TAT	0.25	0.34	0.56	0.94	0.94	0.61
Miscanthus	ROTA	13%	6%	15%	−7%	−2%	−34%
	IRR	11%	7%	13%	NA	NA	NA
	PBP	8.0	7.8	6.8	73.0	26.0	NA
	TAT	0.25	0.34	0.56	0.94	0.94	0.61
Switchgrass	ROTA	13%	6%	15%	−6%	−2%	−34%
	IRR	11%	7%	14%	NA	NA	NA
	PBP	7.9	10.2	6.7	51.0	24.0	NA
	TAT	0.25	0.34	0.56	0.94	0.94	0.61

IRR, internal rate of return; *PBP*, payback period; *ROTA*, return on total assets; *TAT*, total assets turnover.

most suitable for climates that allow full plant operation for more than 6 months per year. Also large CHP is preferable to small CHP applications due to significant economies of scale. Pyrolysis oil and second-generation ethanol are emerging as the most promising new technologies. However, they are still at a development stage, not yet financially justified without generous state support.

The route driving away from mineral energy sources (oil and coal) is paved by national renewable energy programs with outstanding attention paid to biomass sources. This is reinforced by rapid technological development toward cheaper and more efficient biomass transformation processes and inevitably leads to a new market state regarding biofuels and bioproducts in general.

Economic viability is a necessary condition for the adoption of new technologies, but it is not the sole criterion. Today, societies need to make decisions based on the examination of more complex combinations of priorities. Social and environmental considerations may be more important than financial viability. Therefore OPTIMA went one step further and examined the combination of economic, social, and environmental implications of crop cultivation in both marginal and standard agricultural lands, assuming a multiplicity of cross-disciplinary criteria to measure the combined effect of various conflicting objectives.

8.5.5 Socioeconomic Analysis

8.5.5.1 Employment Effects

This section discusses the employment effects in terms of total job equivalents per value chain using the reference units from the OPTIMA analysis (Section 8.5.1). It also provides detailed information for how these jobs are structured in terms of direct, indirect, and net-induced per value chain.

Fig. 8.8 shows the total (direct, indirect, and induced) job equivalents for the under study value chains. As expected, jobs increase as scales and amount of annually required biomass supply increase. Giant reed-fueled value chains always exhibit a lower number of jobs as the crop yields at marginal land are 17.5 $t\,ha^{-1}\,yr^{-1}$, while miscanthus yields are 14 $t\,ha^{-1}\,yr^{-1}$, and switchgrass is much lower at 8.75 $t\,ha^{-1}\,yr^{-1}$, respectively.

In domestic heat the total number of job equivalents is around 2–2.3 with the number of direct jobs being in the range of 0.3 and the net additional induced jobs being around 2.

In small-scale CHP, direct jobs are approximately equal to the induced ones, deriving mainly from biomass production (Christian and Riche, 1999). In this value chain (as the previous one was rather small and differences among crops were negligible) the influence of yields on the number of job equivalents shows differentiation in particular for giant reed as it exhibits a much higher yielding capacity (17.5 $t\,ha^{-1}\,yr^{-1}$) than the other three,so less land is required to secure fuel supply for the power plant with a subsequent lower number of direct job equivalents. The respective numbers of direct job equivalents range from 12 in the giant reed-fueled chain, to 15 in miscanthus, and 22 in switchgrass.

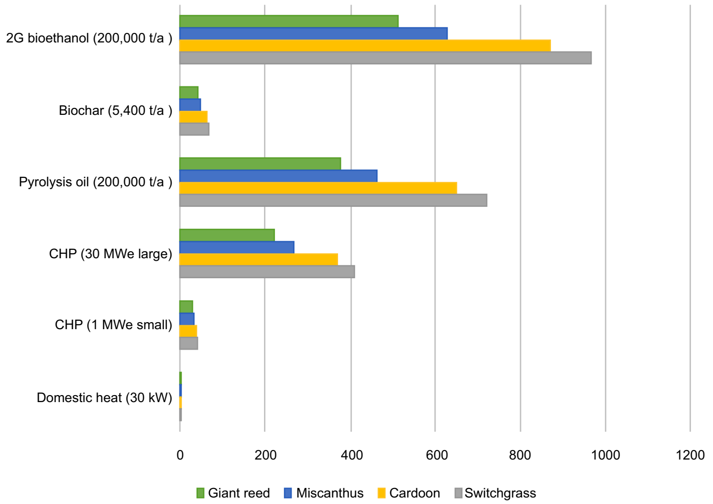


Figure 8.8 Full job equivalents for each of the studied value chains. *2G*, second-generation; *CHP*, combined heat and power.

The number of total job equivalents for the biochar value chain ranges from 52 (giant reed) to 80 (switchgrass) with the same logic for the influence of yields in the direct job equivalents. Net additional induced jobs have been estimated at 2 for domestic heat, 18 for small-scale CHP, and 21 for biochar (accounting mostly for equipment manufacturers, maintenance, and service).

It is clear that as scales and respective amounts of required biomass supply increase, the direct jobs have the major share in the total number of job equivalents as they reflect the large amounts of raw material. Net additional induced jobs have been estimated at 26 in small-scale CHP, 28 in pyrolysis oil, and 29 in second-generation bioethanol (accounting mostly for equipment manufacturers, maintenance, and service).

8.5.5.2 Social Sustainability

Social sustainability evaluates the impacts of the value chain on society and rural development. The analysis in OPTIMA took into account the following criteria:

- Contribution to rural economy: Employment is a major issue in rural economies. Certain value chains may induce more regional job creation, stimulating the rural economy, while other value chains may be more directed to large-scale industry, often in the hands of international players/multinationals.
- Local embedding: The capacity of the local economy to develop and operate a full value chain or part of it (e.g., in the OPTIMA case the production of perennial crops).
- Proximity to markets: The indicator expresses the difference between a more local approach with low distances (feedstock converted and consumed locally) on the one side, and on the other side a more international/industrial approach where the feedstock is transported to large industrial sites or to harbor areas to be exported.

Table 8.5 **Performance of the under study value chains in social sustainability**

	Contribution to rural economy	Local embedding	Proximity to markets
Domestic heat	*	*	*
CHP (1 MWe small)	*	*	*
CHP (30 MWe large)	**	*	*
Pyrolysis oil	**	***	***
Biochar	**	***	***
2G bioethanol	**	***	***

*, higher rank; **, medium rank; ***, lower rank; *2G*, second generation; *CHP*, combined heat and power.

All under study perennial crops are considered highly beneficial to the three social sustainability criteria as they are expected to diversify farming activities, provide new opportunities for farmers and the rural economy, and facilitate improved infrastructure for harvesting, storage, transport, and logistics.

Table 8.5 illustrates the performance of the under study value chains in the social sustainability criteria.

Domestic heat and small-scale CHP rank high in all three criteria, as both the full value chain and the end product offer very good prospects to the rural economy with the production of perennial crops, the manufacturing and/or increased market for biomass boilers/related equipment, and the provision of service for their operation and maintenance.

Large-scale CHP value chains rank moderate in the contribution to the local economy as they can be beneficial for the local economy in terms of partially supplying the plant with raw material and generating jobs for building and operating the plant while the major part of biomass supply and plant equipment is brought into the region from other regions or countries.

The value chain ranks high in embedding to the local system and proximity to markets as it can provide heat for district heating (if available) and electricity to the grid or industrial sites/businesses.

The value chains of pyrolysis oil, biochar, and second-generation bioethanol rank low in embedding to the local system and proximity to markets as they are larger plants and the major part of their raw materials and respective sales of end product will be from outside the region/local economy.

8.5.6 Integrated Sustainability Assessment

Integrated sustainability assessment in OPTIMA was based on the methodology of ILCSA (Keller et al., 2015). The ILCSA procedure follows the principle of life cycle thinking and builds on and extends the procedure defined for LCAs in ISO standards 14040:2006 and 14044:2006 (ISO, 2006a,b). It addresses impacts on sustainability throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal. The goal of ILCSA is to provide comprehensive ex-ante decision support from a sustainability point of view in the process of establishing new technologies, processes, or products.

Basically, a common set of scenarios is subjected to an assessment of various aspects of sustainability (environmental, economic, and socioeconomic), based on the same settings and definitions. Indicators and results from these separate assessments are subsequently combined to form an overall picture.

The integrated sustainability assessment is based on a life cycle comparison of providing a certain product either from biomass by processes studied in OPTIMA or from mostly fossil resources by conventional processes. These life cycle comparisons were comprehensively assessed regarding many sustainability aspects, which led to results for many sustainability indicators. The results of the life cycle comparisons to equivalent conventional product life cycles are shown in Table 8.6. Particularly in the socioeconomic assessment, these indicators represent only a small selection of all possible indicators.

The comparison of OPTIMA scenarios to conventional scenarios shows rather similar patterns of advantages and disadvantages. Thus improvements of sustainability in some aspects will always come at the cost of additional impacts regarding other aspects.

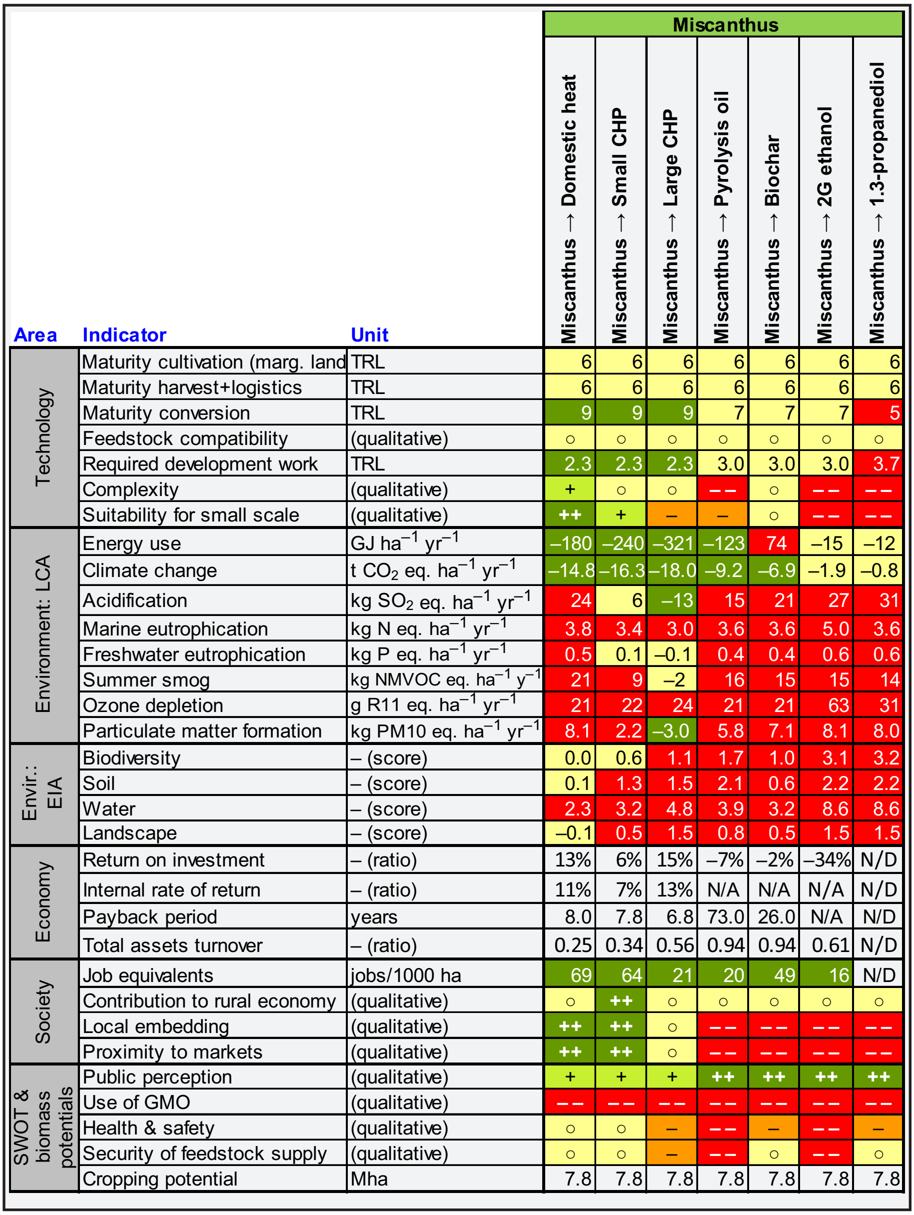
The following general strengths and weaknesses of providing energy and material products from perennial biomass cultivated on marginal land can be seen although they do not apply to all scenarios:

Environment: Most scenarios achieve a mitigation of global warming and reductions in the depletion of fossil energy resources. At the same time, most other environmental impacts are worse than for conventional provision of the same products. This effect is commonly seen for products of intensive agriculture. The impact on water resources is negative if irrigation is needed.

Economy: Economic performance largely depends on the use option of the biomass. Some scenarios can compete well with equivalent conventional options; others are not expected to be profitable under the assessed conditions. Thus profitability is neither a general strength nor a weakness of cultivating and using perennial grasses but has to be analyzed in detail.

Society: Regionality has strong implications for social impacts and can be made a strength of the assessed value chains. This is reflected in the indicators contributing to the rural economy, local embedding, and proximity to markets. The scenarios show high advantages if regionally produced biomass is used in comparatively small-scale units. If large-scale conversion plants are involved, impacts are not as favorable. Job creation is another advantage of the OPTIMA scenarios. A major contribution to job creation is also expected from a general strengthening of the rural economy.

Table 8.6 Overview of sustainability assessment results



			Miscanthus						
Area	**Indicator**	**Unit**	**Miscanthus → Domestic heat**	**Miscanthus → Small CHP**	**Miscanthus → Large CHP**	**Miscanthus → Pyrolysis oil**	**Miscanthus → Biochar**	**Miscanthus → 2G ethanol**	**Miscanthus → 1.3-propanediol**
Technology	Maturity cultivation (marg. land	TRL	6	6	6	6	6	6	6
	Maturity harvest+logistics	TRL	6	6	6	6	6	6	6
	Maturity conversion	TRL	9	9	9	7	7	7	5
	Feedstock compatibility	(qualitative)	○	○	○	○	○	○	○
	Required development work	TRL	2.3	2.3	2.3	3.0	3.0	3.0	3.7
	Complexity	(qualitative)	+	○	○	– –	○	– –	– –
	Suitability for small scale	(qualitative)	++	+	–	–	○	– –	– –
Environment: LCA	Energy use	$GJ\ ha^{-1}\ yr^{-1}$	–180	–240	–321	–123	74	–15	–12
	Climate change	$t\ CO_2\ eq.\ ha^{-1}\ yr^{-1}$	–14.8	–16.3	–18.0	–9.2	–6.9	–1.9	–0.8
	Acidification	$kg\ SO_2\ eq.\ ha^{-1}\ yr^{-1}$	24	6	–13	15	21	27	31
	Marine eutrophication	$kg\ N\ eq.\ ha^{-1}\ yr^{-1}$	3.8	3.4	3.0	3.6	3.6	5.0	3.6
	Freshwater eutrophication	$kg\ P\ eq.\ ha^{-1}\ yr^{-1}$	0.5	0.1	–0.1	0.4	0.4	0.6	0.6
	Summer smog	$kg\ NMVOC\ eq.\ ha^{-1}\ y^{-1}$	21	9	–2	16	15	15	14
	Ozone depletion	$g\ R11\ eq.\ ha^{-1}\ yr^{-1}$	21	22	24	21	21	63	31
	Particulate matter formation	$kg\ PM10\ eq.\ ha^{-1}\ yr^{-1}$	8.1	2.2	–3.0	5.8	7.1	8.1	8.0
Envir.: EIA	Biodiversity	– (score)	0.0	0.6	1.1	1.7	1.0	3.1	3.2
	Soil	– (score)	0.1	1.3	1.5	2.1	0.6	2.2	2.2
	Water	– (score)	2.3	3.2	4.8	3.9	3.2	8.6	8.6
	Landscape	– (score)	–0.1	0.5	1.5	0.8	0.5	1.5	1.5
Economy	Return on investment	– (ratio)	13%	6%	15%	–7%	–2%	–34%	N/D
	Internal rate of return	– (ratio)	11%	7%	13%	N/A	N/A	N/A	N/D
	Payback period	years	8.0	7.8	6.8	73.0	26.0	N/A	N/D
	Total assets turnover	– (ratio)	0.25	0.34	0.56	0.94	0.94	0.61	N/D
Society	Job equivalents	jobs/1000 ha	69	64	21	20	49	16	N/D
	Contribution to rural economy	(qualitative)	○	++	○	○	○	○	○
	Local embedding	(qualitative)	++	++	○	– –	– –	– –	– –
	Proximity to markets	(qualitative)	++	++	○	– –	– –	– –	– –
SWOT & biomass potentials	Public perception	(qualitative)	+	+	+	++	++	++	++
	Use of GMO	(qualitative)	– –	– –	– –	– –	– –	– –	– –
	Health & safety	(qualitative)	○	○	–	– –	–	– –	–
	Security of feedstock supply	(qualitative)	○	○	–	– –	○	– –	○
	Cropping potential	Mha	7.8	7.8	7.8	7.8	7.8	7.8	7.8

Results are shown for cultivation on marginal land and standard conversion conditions. Categorization and respective coloring of quantitative results reflect differences to the conventional alternative.
GMO, genetically modified organism; *N/A*, not applicable; *N/D*, no data; *TRL*, technology readiness level.

8.6 Conclusive Remarks

This chapter outlined the environmental, economic, and socioeconomic aspects of perennial grass production and use, with an emphasis on cultivation in Mediterranean marginal land. The assessed impact pathways rely primarily on management intensity and crop traits, and second on the processing and use systems. Perennials can be considered as more environmentally acceptable crops than annual energy crops, since the requirement of inputs (fertilizers, pesticides) is low and the longer permanence period in the ground benefits erodibility, biodiversity, and use of resources. In addition, the substitution of fossil fuels and materials through the use of perennials can lead to energy savings and reductions in greenhouse gas emissions, but regarding other environmental categories, e.g., acidifying emissions, negative impacts can be witnessed in comparison with conventional routes. When irrigation is needed the impact on water resources is also detrimental to the sustainability of the value chains. Their economical exploitation is affected by yields and by the end use options. Production in small-scale units provides benefits toward job creation and the rural economy.

Acknowledgments

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Perennial Grasses for Bioenergy and Bioproducts

Production, Uses, Sustainability and Markets for Giant Reed, Miscanthus, Switchgrass, Reed Canary Grass and Bamboo

Edited by Efthymia Alexopoulou

Perennial Grasses for Bioenergy and Bioproducts brings together a team of international authors to explore the current utilization, sustainability, and future perspectives of perennial grasses in the bioeconomy.

The book starts by examining the role of these crops as feedstock for bioenergy, in particular advanced biofuels, and bioproducts. It then offers five chapters, each covering one perennial grass type, namely, giant reed, miscanthus, switchgrass, reed canary grass, and bamboo, including their breeding, cultivation, harvesting, pretreatment, economics, and characterization. The book goes on to present the thermochemical conversion pathways for this type of feedstock. Finally, the last chapter explores the issues concerning sustainability of perennial grasses, including their production in marginal lands.

This thorough overview is a helpful reference for engineering researchers and professionals in the bioenergy sector, whose understanding of feedstock characterization, sustainability, and production is critical to the development of conversion technologies. Those in the industrial crops sector will find issues surrounding crop production, which can guide their feedstock cultivation, harvesting, and pretreatment for a specific conversion process or end use. The book is also a useful resource for instructors and students in Master's and PhD programs in the area of biomass and energy crops. Policymakers and government agents involved in regulating the bioenergy and bioproducts sector will find comprehensive information to guide their decision-making.

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