CHAPTER 19

Creating Dedicated Bioenergy Crops

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Bioenergy is one of the current mechanisms of producing renewable energy to reduce our use of nonrenewable fossil fuels and to reduce carbon emissions into the atmosphere. Humans have been using bioenergy since we first learned to create and control fire, burning manure, peat and wood to cook food and generate heat (Fig. 1). Now that we are trying to scale up this activity to millions of acres or hectares, we are faced with the challenge of developing dedicated crops that have all the traits necessary for economic viability and profitability. Bioenergy crops will represent only one of many solutions to this problem, with significant untapped energy available from solar radiation, wind and waves.

Bioenergy crop plants

Many types of plants are currently under development as dedicated biofuel crops. These range from annuals to perennials, from existing food crops to wild and undomesticated species, and from grain crops to cellulosic or biomass crops. As with our current energy demand that is satisfied by multiple fossil fuels and a wide array of renewable energy sources, future needs will be met by a wide range of biofuel crops that represent the diversity of plant form and function found on the planet. Some of these crops have already been domesticated, leading to rapid development and deployment of simple conversion processes, such as fermentation of corn grain into ethanol. Other plant species are wild and undomesticated, often with weedy traits that allow them to become invasive when they escape into highly sensitive landscapes and habitats, such as wetlands, lakes or rivers. Male sterility is often suggested as a solution to reduce potential invasiveness, but sterility systems are not perfect, often breaking down under some environmental conditions, or creating unforeseen susceptibilities to pests.

Many of the current perennial bioenergy crops have been used as forages for years, including both hay and pasture production. As these crops move into bioenergy production systems, their management must change to adapt to an energy production system: e.g. one harvest per year (in most cases), allow nutrients to recycle into roots prior to harvest, delay harvest until post-senescence dry down, and emphasis on high densification harvesting and storage systems. These changes in harvesting and management have led breeders to develop new or altered breeding objectives for these plants, some of which are shared between forage and energy, leading to dual-purpose varieties, but some of which are significantly different, leading to dedicated forage or energy types.

Several annual crops have already been deployed as biofuel crops, most notably corn grain fermented to ethanol

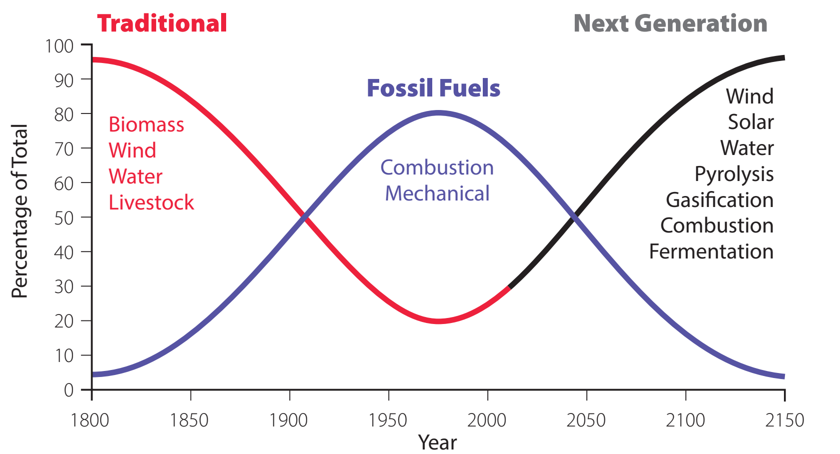

Figure 1. Approximate energy timeline showing human transitions from traditional energy sources to fossil fuels to next-generation renewable fuels.

as a transportation fuel. During the past 100+ years, plant breeders have dramatically increased the harvest index of annual grain crops such as corn, sorghum, wheat, barley and rice, so that the grain makes up more than 50% of aboveground plant production (Austin et al. 1980; Russell 1991). Fermentation of grain crops converts starch to ethanol, leaving behind a fat- and protein-rich grain residue, or distillers' grain, which is an inexpensive feed additive for livestock. Challenges to utilize distillers' grain for livestock feed include logistics of transportation and the need to balance diets to the unique characteristics of these residues. Annual crops also produce significant quantities of crop residue, largely in the form of stover or straw. These residues are often termed "cellulosic" biomass because they consist largely of cell wall material, rich in cellulose and hemicellulose. While recent trends in sustainable agriculture have moved toward using crop residues for soil and water conservation, there is considerable movement toward converting some of these residues into energy (Shinners et al. 2010).

Sugarcane represents the premier perennial grass for bioenergy production, largely due to its production of highly fermentable sugar, its high biomass yield, and the existing infrastructure for production and processing. This grass is one of the principal drivers of the highly successful Brazilian bioeconomy (Tew and Cobil 2008). Numerous perennial herbaceous plants are being investigated for biofuel development, with the majority of U.S. government funding going toward switchgrass and miscanthus. Switchgrass was chosen by the U.S. Department of Energy in 1992 as a model plant to represent this group (Sanderson et al. 2007). This choice was based on relatively high biomass yields across a broad region, its status as a native plant, adaptation to many types of marginal soils, relatively high drought tolerance, and an existing seed industry with simple seed processing requirements. Since that decision, switchgrass biomass yields have increased by 30–40%, about half due to proper choice of locally adapted varieties and half due to dedicated breeding for higher yields of biomass (Fig. 2). Efforts to develop miscanthus into a bioenergy crop are focused on three species: *Miscanthus sinensis*, *M. saccariflorus* and *M.* x *giganteus*. The latter species, giant miscanthus, is a very rare plant in nature, formed as a sterile progeny of the other two species. It has already been deployed as a bioenergy crop for combustion in Europe on a limited scale. Because it is sterile, producing no viable pollen or seeds, it is propagated only by rhizomes or stem bases. As such, propagation materials of superior genotypes are somewhat limited in availability and considerably more expensive than seeded varieties.

Neither switchgrass nor miscanthus is the best choice on all lands, due to adaptation issues and large-scale deployment of one species creates the potential for massive disease or insect problems. Thus, many other perennial plants are also undergoing development as biofuel crops on a more limited or regional basis. Some examples include big bluestem, indiangrass and prairie cordgrass in the prairie regions of North America; elephantgrass and giant reed in humid, subtropical regions; giant wildrye for arid grassland areas; and alfalfa in regions where it is well adapted. Alfalfa

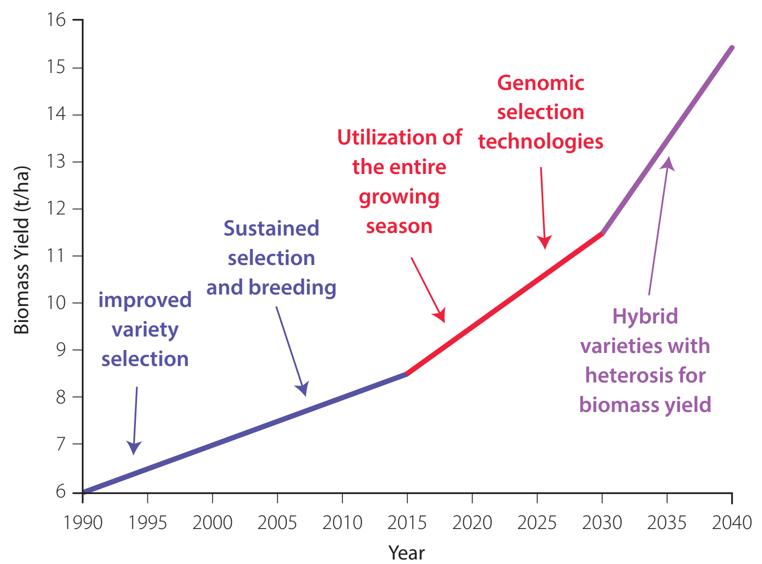

Figure 2. Timeline for switchgrass improvement since the beginning of the U.S. Department of Energy Bioenergy Feedstock Development Program. The blue line represents documented increases in biomass yield. The red and purple lines represent predictions based on current and realistic changes to breeding objectives, breeding methods, and the technologies that are available to breeders. (for T/acre multiple by 0.45)

offers a distinct advantage over grasses, because its biomass can be split into two revenue streams: leaves can be stripped from the plant and converted into a high-protein feed while stems can be converted into energy via one of several different conversion methods (Anderson et al. 2008). Alfalfa has the additional benefit of nitrogen fixation, eliminating one of the major inputs and expenses of energy-grass production.

Numerous perennial woody plants are also undergoing development as bioenergy crops, including poplars, willows and pines (Davis 2008; Peter 2008; Smart and Cameron 2008). These are generally fast-growing plants that are propagated as single genotypes into highly homogeneous plantations for uniform production and harvesting. Growth cycles range from 5–20 years, with the shorter growth cycles used for plants that can regenerate new stems for multiple growth and harvest cycles from a single plantation. These plants produce large quantities of cellulosic biomass that can be converted into energy in one of several methods described below. In addition, many woody plants have seeds with high oil content that lend themselves to production of an annual seed crop that can be harvested for oil extraction and conversion to biodiesel by transesterification. Examples of these trees or shrubs include: oil palm, *Jatropha* and *Pongamia* (Halford and Karp 2011).

Figure 3. Genetic diversity in plant morphology, flowering time, and biomass yield in a typical switchgrass breeding nursery.

How do we develop dedicated biofuel crops?

Existing varieties of domesticated crops and natural varieties or ecotypes of undomesticated plants have been used in the early studies of biofuel crop development and conversion to energy. Development of dedicated varieties requires several years of selection, breeding and seed or rootstock multiplication. The basic breeding process involves the following steps:

- Identify and assemble desirable plant materials. This involves collection of plant materials that have some desirable levels of adaptation and agronomic traits for the region and the mode of production. The foundation plant materials must possess high levels of genetic diversity, sufficient to form a basis for identifying and selecting superior plants (Fig. 3).
- Crossing parental plants or populations. Initial crosses are made among many different parents to create genetic recombinations in the progeny. Parents of crosses are typically selected for different traits in an attempt to combine two or more desirable traits into a single genotype or population of plants.
- Establishment of uniform nurseries. Nurseries should be established on representative soils using real-world or accurately simulated management and harvesting methods.
- Selection of the best plants, based on several traits that represent both agronomic and silvicultural aspects of production and conversion efficiency, as measured by quality traits in the laboratory. In many cases, quality traits are very similar or nearly identical to quality traits used in the forage-livestock industry. For example, highly digestible forages for livestock production are generally highly fermentable for ethanol production systems. Modern switchgrass varieties with increased digestibility are being promoted as dual-purpose varieties. Conversely, thermochemical conversion platforms favor energy-rich plant compounds, such as lignin and phenolics, leading to completely opposite breeding objectives for forage crops vs. energy crops.
- Selected plants are crossed with each other to create the next generation of plants for evaluation (Fig. 4). For vegetatively propagated crops, one or two of the best plants can be considered for direct release and marketing. Selected genotypes or candidate varieties are tested in replicated field trials and multiple locations for several years prior to any decision to enter the marketplace.
- Seed or vegetative propagules must be multiplied under controlled and isolated conditions to generate sufficient material to meet market demand. Many growers specialize in this type of activity.
- Numerous laboratories are developing genetically modified switchgrass, using genetic engineering technologies to change the expression of existing genes within switchgrass. Most of these efforts are focused on downregulating genes in the lignin pathway, reducing the cost of pretreatment and making structural carbohydrates more available to fermentation (Chen and Dixon 2007). Additional objectives will include altering flowering time, creating sterility that can be turned on or off on demand, and improving stress tolerances.

Figure 4. Crossing selected switchgrass plants in the field.

Biomass yield is generally the most important trait in breeding dedicated bioenergy crops (Perrin et al. 2008). Biomass yield is an amalgamation of many simpler plant traits, such as height, tillering, tolerance to stresses, disease and insect resistance, recovery after cutting or harvesting, persistence and flowering time. If breeders are growing plants in the right types of environments, with frequent exposure to stress factors, and evaluating plants for sufficiently long time periods, all of these traits can be collectively measured when we measure biomass yield over several years of production. Many breeders will add specific sub-objectives to the breeding program, either inoculating plants with a disease pathogen to ensure that a disease challenge has taken place, or selecting plants with a particular morphology that scientific studies have suggested to be an ideal form for biomass production. Additional breeding objectives involve selection against naturally occurring seed dormancy mechanisms, selection for seedling vigor and establishment capacity, and selection for high biomass yield under low-nutrient or marginal-soil conditions. The trick for the breeder in each of these cases is to develop a screening method that allows evaluation of thousands of plants under the conditions required, e.g. acid soils, low soil N, severe competition with annual weeds, etc.

The next generation of improvements to breeding programs is expected to bring about more rapid rates of improvement. In switchgrass, southern varieties are considerably later in flowering than northern varieties, so breeders are currently selecting southern varieties for winter survival in an effort to keep them growing (and accumulating dry matter) as long as possible (Fig. 2). The southern lowland-type of switchgrass is always superior to the northern upland-type, but there is a need for more intensive breeding efforts to create further improvements in northern climates where lowland types are very rare (Table 1). New DNA sequencing technologies have provided a mechanism to use modern genomic tools to speed up breeding programs, especially for complex traits such as biomass yield. These two innovations, combined with the promise of developing superior hybrids, suggest that we can realistically double the rate of gain for biomass yield of switchgrass and perhaps other species (Fig. 2). Hybrids between upland and lowland varieties are capable of providing a rapid boost in biomass yield, speeding the process of creating economically viable crops (Table 2).

Table 1. Biomass yield of upland and lowland ecotypes of switchgrass in three regions of the USA.

Region	Upland type	Lowland type	Percentage change
	t/ha	*t/ha*	*%*
Southern USA	5.5	13	137
Central USA	11.0	15.7	43
Northern USA	9.8	12.3	26

(for T/acre multiply by 0.45)

Table 2. Biomass yield of a switchgrass hybrid and its parents.

Genotype	Biomass yield
	t/ha
Kanlow (lowland type)	14.7
Summer (upland type)	12.4
K x S (F1 hybrid)	20.3

(for T/acre multiply by 0.45)

Some breeding programs are also selecting plants for quality traits that enhance the efficiency of fermentation. This is a time-consuming activity that draws funds and time away from the central breeding objective of increasing biomass yield. Improving biomass quality has a high potential payoff in fermentation systems to produce ethanol, due to the negative effects of lignin locking up the energy in cellulose and hemicellulose (Vogel and Jung 2001). This approach has significant synergies with forage breeding in which lignin reductions have a direct impact on increasing forage quality and improving meat or milk production. Furthermore, increasing fermentability reduces the need for energy supplementation in forages and for pretreatment time and expense in biofuel crops. Regardless of the conversion method, plant breeders are beginning to concentrate on selecting plants that recycle as much N as possible back to the roots prior to harvest. This involves using appropriate harvest timing, generally following senescence, combined with a routine analysis of tissue N concentrations. To a plant breeder, adding additional traits to a breeding program creates complexity and decreases the rate of gain that can be made for any individual trait. It is not clear today whether this activity will eventually be cost-effective in creating dedicated cellulosic bioenergy crops. For example, delayed harvest is highly effective at reducing the concentrations of Cl and K in leaf tissue, without impacting energy density, creating biomass that causes fewer management problems when burned (Table 3).

Table 3. Effect of harvest season on concentrations of Cl, K_2O, and energy density of reed canarygrass in a one-harvest management system (Tahir et al. 2011).

Harvest season	Cl	K_2O	Energy density
	%	%	KJ/g
Spring	0.76	1.64	17.4
Autumn	0.41	0.77	17.2
Winter	0.02	0.17	17.3

Complexities and competitions

Numerous technologies exist for conversion of cellulosic biomass to energy (Table 4). Combustion is the oldest technology and was one of the earliest to be employed on a production scale. Biomass from perennial grasses and trees can be pelletized to densify the biomass for ease of transportation and co-fired with coal in existing power plants. This technology is becoming increasingly common in the Eastern USA and Canada and in parts of Europe. Regions of Finland have utilized agricultural fields of reed canarygrass in a very successful program to produce an annual supply of biomass for several coal-fired powerplants. Gasification technologies are rapidly growing in Europe, but have so far been limited in North America. Pyrolysis is still a relative newcomer, but holds great promise for producing a suite of hydrocarbons, including products that can be converted into transportation fuels. Fermentation technologies are currently limited to high-sugar crops such as sugarcane and possibly sweet sorghum. Fermentation technologies are currently severely limited by the lack of efficient conversion of five-carbon sugars from the cell wall into simple sugars that can be fermented easily and rapidly by available microorganisms.

Development of sustainable production systems

Table 4. Methods of converting a portion of cellulosic biomass into energy (transesterification applies specifically to oils extracted from high-oil crops).

Conversion method	Product(s)	Principal Advantage(s)
Combustion	Heat and electricity	*Simple, Uses existing technologies*
Gasification	Syngas (CO, H_2, CO_2, H_2O)	*Efficient conversion of biomass to energy*
Pyrolysis	Hydrocarbons and syngas	*Efficient conversion of biomass to energy*
Fermentation	Ethanol or butanol	*Direct production of transportation fuels*
Transesterification	Biodiesel	*Direct production of transportation fuels*

demands that biofuel crops be produced in a manner that does not compete with food crops. Producing more renewable energy or more sustainable energy does humanity little good if it reduces food production. Many agronomic, breeding and genetics efforts to develop new energy crops are focused on marginal lands that are not optimal for food production. These lands include saline or acidic soils, droughty regions, chronically wet soils, or lands that are currently set aside for conservation purposes, e.g. the Conservation Reserve Program in the USA. Species choice is critical on some of these sites, such as using highly saline-tolerant species such as prairie cordgrass on saline soils (Table 5). Reducing inputs, such as fertilizers and pesticides, is frequently cited as a mechanism to reduce input costs and improve sustainability and economics of bioenergy crop production. Agronomists and breeders need to constantly monitor and consider both societal and economic trends to design optimal production schemes and breeding objectives for developing dedicated bioenergy crops. The most favorable and sustainable bioenergy crops of the future will be those that require minimal inputs without depleting soil and water resources, have sufficient biomass to provide an economic incentive to growers, have favorable chemistry to assist in the reduction of CO_2 emissions, and have a highly positive net energy balance (high ratio of energy produced relative to energy required for production, harvesting and transportation).

Table 5. Salinity tolerance of prairie cordgrass and switchgrass measured with and without saline growing conditions (Kim et al. 2011).

Plant species	Salinity level	Plant height	Number of tillers	Shoot dry mass	Root dry mass
	mM NaCl	cm	#	g	g
Prairie cordgrass	0	81	10	25	12
Switchgrass	0	102	15	30	14
Prairie cordgrass	100	26	7	4	3
Switchgrass	100	14	4	1	<1

One additional effect of bioenergy research has been an indirect reduction of scientific and developmental research on crop and livestock production agriculture. Most plant scientists working on bioenergy crops have significantly reduced (or completely eliminated) their research and outreach efforts on forage or grain crops to focus on bioenergy. This is largely in response to governmental funding programs throughout the world, focusing funding and time away from food and livestock production and toward bioenergy. It remains to be seen what long-term effects these funding decisions may have on crop and livestock agriculture, especially at a time when increasing human population size is putting additional pressure on development of more efficient food production systems.

Conclusion

Plant scientists and engineers are working together to rapidly improve both domesticated and undomesticated species to create more useful and viable bioenergy crops. Meeting the world's needs requires agronomic and genetic improvements in numerous species to fit into a range of environmental niches and conversion platforms that will be employed to produce bioenergy. With dedicated and concentrated efforts, long-term efforts can lead to large payoffs toward development of improved varieties and production systems. Through a combination of sustainable production practices and improved genetics, biomass yields of dedicated bioenergy crops could be doubled by 2040, creating huge opportunities to capture photosynthesis to power a global bioeconomy.

References available online at www.farmwest.com

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Forage Art

"Kuh, Stier und Weide" (cow, bull and range land); Vocational School For Agriculture, Althofen, Austria, 2009 PHOTO BY A. GUERINO