GROWTH AND PRODUCTION OF HERBACEOUS ENERGY CROPS

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Summary

Plants are, in essence, real-time solar energy collectors. After being harvested, their biomass can potentially be converted into liquid fuels or other important energy forms. But, if we wish to produce significant amounts of biofuels from plants, what crops should be used, what conversion technologies are available, and what constraints must be addressed? This chapter provides an assessment of where we stand in 2009 in efforts to answer those questions. Only those technologies and systems that can produce biofuels with positive net energy yields - with minimal negative environmental, ecological, or food-supply impacts - should be considered.

"First generation" biofuels (ethanol and biodiesel) come from grain, sugar, and oil-seed crops that generally require large inputs, incur significant environmental impacts, and can be used for food. Perennial species that are being considered as feed stocks for "second generation" biofuels can often be grown with modest inputs and lower environmental impacts; therefore, they are preferred as energy crops over annual species and food crops. At least they will be preferred when "cellulosic biofuel" can be made commercially from their cellulose-rich biomass. Herbaceous species, especially some members of the grass family, have advantages over woody species as energy crops in many settings. Multi-species plantings, or consortia of species, may provide some advantages over monocultures.

Attributes of ideal energy crops would include: ready establishment and management, ease of genomic manipulation, more efficient conversion into liquid fuels, and provision of key ecosystem services. Technologies that can convert cellulosic biomass into liquid biofuels (e.g. ethanol or biodiesel) on a commercial scale have been elusive, but progress is being made. Land use, logistic, and economic factors must also be taken into consideration when devising sustainable energy cropping systems.

1. Introduction

All developed nations are highly dependent on fossil fuels; and developing nations appear headed down the same path. Yet scientists, economists, and policy makers warn of over-reliance on fossil energy sources. The risks of fossil-fuel dependency include:

- The inevitable exhaustibility of these resources coupled with an indefinite capacity for population growth.
- Geopolitical turmoil, which can be both a cause for and an effect of volatile energy prices.
- Environmental impacts associated with fossil-fuel extraction and distribution, e.g. oil spills, strip mining, methane releases, etc.).
- Environmental (and geopolitical) impacts associated with releasing fossilized carbon into the atmosphere; such consequences include:

- Lowered oceanic pH, affecting life processes in marine (and freshwater) ecosystems.
- Rapid global climate change, threatening stability of Earth's life-support systems.
- Increased mean sea level, submerging low-lying areas that often are highly populated.

These factors, maybe especially those affecting life-support functions of the planet, argue strongly for new energy sources to power human society. Several renewable, non-polluting, or much-less-polluting sources of energy are already powering human society to a limited extent. Other sources are under development and will likely become part of nations' "energy mix". This report will focus on one of those sources – plants, which can harvest the sun's energy and use it to synthesize biomass. That energy-rich biomass, in turn, can be collected and converted into more immediately useful forms, such as heat, electricity, or transportation fuels.

1.1 . The Biorefinery Concept and Energy Crops

The sun delivers to the Earth more than enough energy to power human activities – not just for life support (food, clothing, shelter, etc.) but also for the much more energetically expensive, non-biological activities of industry, transportation, communication, etc. However, that energy is diffused over a very large area. Capturing sufficient sunlight, converting it into other energy forms, and storing that energy for times when the sun doesn't shine present major technological and/or economic challenges. So, for example, electricity can be made and delivered more cheaply and dependably to most locations when produced from coal than from sunlight; but changes in photovoltaic and energy storage technologies, in the price of coal, or in policies that favor renewable energy could quickly begin to favor photovoltaic energy.

Photovoltaic or solar-thermal technologies aside, we have available a biological mechanism for converting sunlight into energy-rich materials. Photosynthesis is, of course, the process by which plants use the sun's energy to generate complex chemical forms (sugars, lipids, proteins, etc.) from simple molecules (CO_2, water, minerals, etc.). Some futurists predict a global economy in which dedicated crops are grown across major portions of the landscape to be harvested and converted into liquid fuels, heat, and electricity. Processing points for biomass-to-bioenergy conversions are likely to be distributed across the landscape. The conversion facility may be a power plant, where biomass is burned to make electricity; or it may be a "biorefinery", where the feedstock is converted into liquid, gaseous, or solid fuels, which are then distributed to end users.

1.2 . Historical View of Interest in Energy Cropping

Biomass has been used for energy purposes (heating, cooking, lighting, etc.) since prehistoric times; but interest in energy cropping, i.e., growing crops on land dedicated to production of feedstock for a biorefinery, is a relatively recent development. Over the centuries, farmers in many parts of the world have planted some crops, e.g., oat (*Avena sativa*) and forages, to feed draft animals. At some level, that is not too different from the notion of growing switchgrass (*Panicum virgatum*), maize (*Zea mays*), or soybean (*Glycine max*) to make ethanol or biodiesel for transportation fuels. What is decidedly different about the notion of energy cropping and biorefineries today are the scale and intensity of the enterprises.

Many proposed systems are still in pre-commercial research or pilot stages; but some energy crops are already proven in the market place, and their use has been rapidly expanding. The conversion of large areas for growing oil palms (*Elaeis* spp.) to produce biodiesel is one example. Ethanol production from sugarcane (*Saccharum* spp.) in Brazil is another large-scale energy cropping enterprise. The diversion of maize grain into ethanol production in the USA is a third.

Energy cropping received some interest in the USA in the 1970s, when petroleum-exporting countries temporarily reduced production, causing oil prices to escalate. The resultant burst of biofuels research and entrepreneurial activity focused heavily on developing small-scale, on-farm systems – not on regional-scale biorefineries. The energy cropping initiatives of the 1970s proved unsustainable. Fuel ethanol could not be produced on-farm at a cost that could compete with petroleum, especially when oil prices returned to pre-crisis levels. This was in an era when oil was <US$10 per barrel.

In the USA, interest in research on energy cropping began to revive in the 1980s. The US Department of Energy (DOE) Oak Ridge National Laboratory first funded research on woody species for energy purposes and then expanded the program to include herbaceous species in 1985. After a five-year, five-institution screening of potential herbaceous energy crops, switchgrass was selected as a “model species” for further study. From 1992 through 2001, DOE funded work on switchgrass that included studies of its agronomy, physiology, breeding, cytology, and potential for exploitation via biotechnology. Workers from the US Department of Agriculture (USDA) began to look at switchgrass for energy purposes during this interval as well.

Work on energy cropping, whether with switchgrass or other species, was curtailed in the USA beginning in 2001 and has only recently begun to regain some momentum. Workers in Europe and other parts of the world, who began to screen herbaceous energy crop types in the 1990s, continued their work apace into the 21st century and gained some measure of primacy in the field as a result.

2. Overview of Energy Crops: Relative Advantages of Various Categories

The “first-generation” biofuel crops have been traditional crops employed to a new end. Maize and oil palm seeds are rich in starch and oils, respectively; and the stems of sugarcane are high in sucrose. Carbohydrates such as starch and sucrose are readily converted into ethanol, which can perform as an alternative fuel for gasoline-powered engines. Oils from oil palm and other oil-seed crops, such as sunflower (*Helianthus annuus*) and soybean are readily converted into products that perform well as fuel in diesel engines. Several of these starch-, sugar-, or oil-based energy crops will be considered below.

The “second generation” of biofuels will come from so-called cellulosic, or ligno-cellulosic feedstocks. The species gaining increasing attention for second-generation energy cropping systems are perennial and can yield high levels of biomass with relatively few inputs. Obviously, the biochemical nature of stems and leaves is quite different than that of seeds. While seeds are typically rich in starch or oils, the stems and leaves of plants are relatively high in cellulose, hemi-cellulose, lignin, and other complex chemical forms. The complexity of these components is a two-edged sword. They are energy-rich but not as readily converted (as are seeds) to liquid fuels such as ethanol or biodiesel.

A major constraint in the development of second-generation, or cellulosic, bioenergy systems is the development of a scalable technology for efficiently converting cellulosic biomass into ethanol or biodiesel. Several technologies have been proven at the bench scale; but, as of this writing, none has been shown to work on a commercial scale. However, several pilot plants are in development, and many in the industry feel “it is just a matter of time” until a suitable technology is proven in the marketplace. Indeed, that technology may have emerged even before this report appears.

2.1. Woody *vs.* Herbaceous Energy Crops

The primary focus of this paper is herbaceous energy crops; but we briefly mention wood because it has long been used as feedstock for energy, and novel wood-based energy systems are appearing. Wood is almost certainly the original bioenergy resource (*see also*: *Perennial Energy Crops: Growth and Management*). Used since prehistoric times for heating, cooking, and illumination, wood is still a primary energy source in many parts of the world. Its ready availability in many places and its energy density (BTUs, calories, or joules per unit mass) make wood a very convenient fuel even outside the home. In the past, wood was used extensively to fire boilers for generating steam to power transportation and industry. Today it is burned alone or co-fired with coal to make electricity. Wood, which is largely ligno-cellulose, can also potentially become a second-generation biofuel source, being convertible into liquid or gaseous forms to help power transportation and other systems.

What are the relative merits of using wood as an energy feedstock when compared to herbaceous species? Ready availability and low cost may sometimes favor wood. In some places, logging operation residues and waste wood from demolitions and manufacturing processes constitute potentially large resources for conversion into energy. In such cases, the energy feedstock is a waste product from some other enterprise. Increasingly though, trees are being grown specifically for their energy content, i.e. as a dedicated energy crop. Energy plantations use improved lines of hybrid poplar (*Populus* spp.), willow (*Salix* spp.), and other tree species that can reach a harvestable stage relatively quickly. The technologies for generating and hauling wood chips – either for pulp or for energy purposes – are well established. In some parts of the USA, woodchips might be a low-cost form of cellulosic biomass, although prices currently vary considerably by region and can be volatile.

The production cycle of woody species in an energy plantation setting is often about five years – the interval from planting to first harvest and/or the time during which coppice re-grows between harvests. This pattern means that energy plantations may require relatively lower annual inputs once they are established, and a series of staggered plantings can create an essentially continuous supply of biomass – a critical feature for a feedstock.

Some research suggests annualized biomass-production and carbon-sequestration potentials of woody biofuels species are similar to those of perennial herbaceous biofuels species. However, other works have shown a decided advantage for some herbaceous species both in yield and in carbon sequestration. If improved woody and herbaceous cellulosic species prove to be essentially equivalent in production potential and carbon sequestration at a site, the decision on which type of energy crop (woody or herbaceous) to plant may ultimately hinge on land-use history and landowner preference. In areas where forestry has been the predominant land use, woody energy crops may prevail. In areas where land has been cleared for field crops or pasture, herbaceous energy crops may be preferred.

2.2. Herbaceous Biomass Crops *vs.* Grain, Sugar, and Oil Seed Crops

A major difference between a biomass crop and a traditional seed/food crop (besides the differences in their biochemical nature) will likely be the volume of yield. This difference almost inevitably weighs in favor of biomass crops, because seed/food crops are typically not harvested in their entirety, even if they are to be used for energy purposes. Rather only selected parts are collected as the economically valuable or desired portion, while much of the biomass is left in the field as straw, stover, or harvest residue. The harvest index (the proportion of the crop's biomass that is the commodity removed in the harvest) for most seed crops is 0.3 to 0.5, while the harvest index of cellulosic energy crops is as close to 1 as harvest will allow.

As a rather broad generalization, grain crops require moderate to high nutrient inputs to develop good yields, while many biomass crops are reasonably productive with lower inputs. Leguminous crops typically do not need nitrogen amendments, but most other grain crops must receive larger amounts of nitrogen than biomass crops to produce the yields commonly reported. The cost of nitrogen fertilizer especially, which is closely pegged to the cost of fossil energy, is a major factor in determining the profitability of grain-based enterprises.

In assessing the sustainability of energy cropping enterprises, the energetic "costs" of all inputs – planting, fertilization, harvesting, transporting, conversion, distribution, etc. – must be balanced against the energy of the output. "Net energy yield" is a key measure of the feasibility or sustainability of an energy crop. Energy yield considers the energy content of a system's output (ethanol or biodiesel) and how much fossil fuel energy must be invested to generate that output and provide it to end users. Although most analyses suggest grain-based energy cropping systems have net positive energy yields, their greater fertilizer requirements and generally lower biofuel yields (see arguments developed above and below) make lower net energy yields essentially axiomatic for first-generation, grain-based energy crops relative to second-generation, biomass energy crops. Several studies have concluded that cellulosic crops can produce five- to ten-fold more energy (as biofuels) as must be consumed in production.

2.2.1. Ethanol from Maize and Other Grain Crops

In the last few years, a significant portion of the maize harvested in the USA has begun to be used to produce ethanol for blending with gasoline. Federal and state policies and incentives have spurred development of large biorefineries to produce ethanol from maize and other grains. The capacity of those biorefineries is currently underutilized because, ironically, as the price of grain has gone up – partially driven by the demand for grain as a biofuel feedstock – ethanol made from grain has become less profitable.

Even in a policy environment favoring production of ethanol from maize, such a system might not be sustainable for environmental reasons. Setting aside the important and not fully resolved issue of whether ethanol from maize provides a positive net energy yield, maize production *per se* poses significant environmental risks. Inherent risks of maize production include the potential for soil erosion and degradation. One major report by DOE (USDOE, 2006) has argued that only perennial crops should be considered for biofuel production, partially because of unsustainable losses of soil that are often implicit in annual cropping systems. A USDA study (NRCS, 2006) on potential effects of energy cropping likewise concluded that soil quality could suffer, especially if maize residues are also removed for energy purposes.

Water quality can suffer as sediments move from maize fields into streams, but water quality can suffer from maize production in other ways. Quantities of nitrogen (and to a lesser extent phosphorus) from a variety of anthropogenic sources flow down the Mississippi River and into the Gulf of Mexico contributing to a seasonal hypoxic "dead zone". Similar seasonal hypoxic patterns occur in other US bodies of water, to include the Great Lakes and Chesapeake Bay. Agriculture – particularly agriculture in upper portions of the Mississippi watershed, which includes much of the US "Corn Belt" – is frequently cited as a major source of the nitrogen that contributes to eutrophication and hypoxia in the Gulf of Mexico.

Additionally, modern methods of pest control – both chemical and biotechnological – have raised concerns about the environmental impacts of maize production. For example, atrazine, which is commonly employed as an herbicide in maize culture, has appeared in surface and groundwater supplies at levels that pose concerns for human and ecosystem health.

Furthermore, making ethanol from maize has at least partially contributed to increased food costs, and economically disadvantaged peoples have borne the brunt of this unintended consequence. In short, many would argue that ethanol made from maize should be considered a stopgap measure, and that better, more sustainable energy cropping systems are needed.

Cool-season cereals such as wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) with their starchy kernels are of potential use as energy crops also, especially in temperate production systems where they might be grown as winter annuals and double-cropped with other species. As with maize and other grain crops, both the starchy grains and the crop residues might be converted to ethanol; but potential use of residues as an energy feedstock again raises concerns about soil quality.

These cereal crops also typically receive the higher inputs associated with many grain crops, leading to questions about economic and environmental fitness. And, of course, each is a human food source or would be grown on land that might otherwise be used for food production.

Sorghum (*Sorghum* spp.), which is a group of warm-season annuals, also has potential in energy cropping systems. Sorghum is unique among energy crops in that various types can be grown for grain, sugar, or biomass. The grain sorghums have lower nutrient requirements and greater water use efficiency than maize, but the general shortcomings of a lower harvest index and higher nutrient requirements than second-generation biomass energy crops remain.

2.2.2. Ethanol from Sugarcane and Other Sugar Crops

Brazil launched a national biofuel program based on sugarcane in 1975. That system would appear to be proving itself economically. The conversion of sugarcane juice into ethanol is relatively simple; the juice is directly fermentable without need to first convert starches into sugar, as must happen with starchy grains used as ethanol feedstocks. Thus, ethanol can be made less expensively from sugarcane than from maize grain.

Besides economic advantages inherent in ethanol-from-sugarcane, Brazil has climate and rainfall patterns that are optimal for growth of sugarcane, a crop of tropical origin. This is not to say that sugarcane culture is without environmental concerns. The USA learned in the sugarcane-producing regions of Florida that water diversions and nutrient runoff could have major adverse environmental impacts.

There is also the concern that diversion of land into biofuel production may compete with food production and/or other ecosystem services. Much of Brazil's new sugarcane land has been created from the *Cerrado*, a biodiverse savannah already heavily transformed by soybean and cattle production. Portions of the Amazonian rainforest are also being cleared to grow more sugarcane.

"Sweet" sorghums, selected for high sucrose content in their stems, could serve in a very similar role as sugarcane in a temperate setting. One of the drawbacks to sweet sorghum as an energy crop is that it has a relatively short storage life before its stems must be processed.

It is hard to envision successful energy cropping enterprises based on sweet sorghum alone, since the conversion facility would be idle for much of the year. Biorefineries that could use multiple feedstocks might be able to incorporate sweet sorghum as one species. In a tropical or long-season environment, sweet sorghum could potentially be produced in multiple, staggered plantings, extending its availability for processing.

Sugar beet (*Beta vulgaris*) is a cool-season annual and the sugar industry's species of choice in temperate environments. It can be harvested in late autumn and stored for a few months (in cold weather) until processed.

The sucrose in sugar beet can be fermented as easily as that from sugarcane or sweet sorghum. As with previous crops, the concerns with sugar beet's use as an energy crop include net energy yield, soil erosion potential, and food *vs.* fuel competition.

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Biographical Sketches

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