
Opportunities for Enhancing the Productivity of Biofeedstocks and Minimizing Inputs: Theory and Practice

STEPHEN P. LONG

*University of Illinois at Urbana-Champaign
Urbana, IL*

Although I am the deputy director of a recently formed joint effort—the Energy Biosciences Institute (EBI)¹ involving the University of California at Berkeley and the University of Illinois at Urbana-Champaign, funded by British Petroleum (BP)—I’ve worked in this area for many years. Much of this presentation comes from that background, rather than from current research². A lot of my work has been on the impacts of global change. When I moved to Illinois in 2000, I set up a unique facility for looking at the impacts of global change on corn and soybean³; my interest in bioenergy comes from seeing biofuels as part of the solution.

FOOD CROPS AS FEEDSTOCKS

At the present time, our main bioenergy crops are sources also of food and feed. The motivation is that we have a huge knowledge base for these species. We have agronomy, genetics and genomics information, and huge germplasm resources. And the infrastructure is in place to make use of extension-service know-how and commercial advisors who are used to dealing with these crops.

Why, then, is there interest in nonfood/nonfeed crops as feedstocks for bioenergy? First of all, generally, they require few inputs. They are perennial and you plant them only once. Optimal nutrition is not important, since you only want the carbon; you are not interested in the protein, which can get in the way of a successful system. So, these

¹<http://www.energybiosciencesinstitute.org/>.

²Many people have helped in this work, most notably graduate students Clyde Beale, Emily Heaton and Frank Dohlman

³<http://soyface.uiuc.edu>

plants have these options plus the fact that, if your main requirement is lignocellulose, it opens up virtually every plant there is as a possible feedstock; there's a huge range of germplasm to be explored. An advantage is that they can grow on non-prime land. We have a wide range of germplasm that can grow in saline soils or on land irrigated with sea water. For example, spartina (cordgrass) will produce about 60 tons of dry matter per hectare per year—about 26 tons per acre—growing in sea water. Perennials, in general, are well suited to sloping, erodible land because they bind the substrate and they can be grown on low-fertility soils. This is one way of avoiding food-versus-fuel issues.

THE IDEAL BIOMASS CROP

The concept of an ideal biomass crop comes from an EU bioenergy network that I was involved in 25 years ago. We said, "If we could start from scratch, what would our ideal crop look like?" I should say that we were thinking about crops that could be put on set-aside or Conservation Reserve Program (CRP) land, or possibly on nonagricultural land that would probably be managed by farmers. This is the shopping list we came up with:

- C4 photosynthesis
- Long canopy duration
- Recycles nutrients to roots
- Low input
- High water-use efficiency
- Sterile, non-invasive
- Can store harvest in field
- Easily removed
- No known pests/diseases
- Uses existing farm equipment

At the top of the list is C4 photosynthesis, because it's the most efficient form of photosynthesis that we know of. Long canopy duration is important; to be efficient, a plant has to capture energy for as much of the year as possible. Within 1 day, the solar energy the earth receives is equal to all the energy that we consume in a whole year. Recycling nutrients to the roots is important, otherwise when you harvest the above-ground material you remove nitrogen and other expensive inputs. Low input is also important, from the environmental aspect and even more so from the economic aspect. Pressure on water resources is ever greater; it's unlikely that biofuel-feedstock crops will be grown with irrigation. Sterility and/or noninvasiveness are necessary to avoid the possibility of new crops becoming aggressive weeds. Huge volumes of feedstocks will be needed to service biofuel-production plants. If biomass can be stored at the farm, just-in-time delivery systems become feasible, circumventing problems of long-term biomass storage. Being easily removed is important because if prices or pressures on food increase, farmers may need the flexibility to quickly change crops. If you grow anything on a large scale, you are not going to escape pests and diseases but, initial lack of such problems is desirable.

And ability to use existing farm equipment again makes a crop a more viable option, potentially part of a more diverse operation.

Corn, the major US crop, is a C4 species. However, it doesn't have long canopy duration. As we approach the summer solstice, most of the Midwest corn is nowhere near covering the soil surface. Neither does it recycle nutrients. On the other hand, it's not invasive and is easily removed.

Another option, which is quite widely used, is short-rotation coppice. Fast-growing trees, such as willows, poplars, eucalypts and bamboos, can be productively harvested on a 3- to 5-year cycle. Although there are no C4 trees, they do have long canopy duration and are good at intercepting radiation. Some trees store nutrients in the roots over winter and others store them in the trunk; nutrient recycling does not occur in the latter. They require moderately low inputs, are generally considered noninvasive, and harvested feedstock can be stored in the field. On the other hand, they are not easily removed, which is a major encumbrance for many growers.

A third option is C4 perennial grasses. This system works well if harvested after it has senesced in the fall. Possible crops include switchgrass, miscanthus, big and small bluestem, Indian grass, and many US-prairie, pampas and steppe species. Considering the "ideal" list above, attributes vary from species to species, but they come closest to the ideal biomass crop.

BIOMASS YIELD

Biomass yield depends on the solar energy available and the efficiency with which the crop intercepts and converts that energy:

$$W_h = S \mathcal{E}_i \mathcal{E}_c$$

where W_h = harvested yield,

S = total solar energy,

\mathcal{E}_i = energy interception efficiency, and

\mathcal{E}_c = energy conversion efficiency.

Issues include how much of the year the ground is covered with green leaves and the efficiency with which intercepted radiation is converted into biomass as determined by photosynthesis and respiration. Of course, the interception efficiency is often a factor of resistance to pests and diseases, and of nutrient availability and use efficiency. The maximum theoretical conversion efficiency is about 6% for C4 plants and about 4.6% for C3 plants. However, no C4 plant reaches that 6% limit. Some reach about 4% in the short term, maybe 3% in the long term. We could gain a great deal of energy by getting closer to the maximum theoretical efficiency.

PERENNIAL GRASSES

Perennials do a better job of absorbing solar radiation than do annuals. As soon as it is warm enough, the former have the reserves to form an active leaf system that intercepts that radiation. Perennial grasses also recycle nutrients efficiently; in the spring they move them from the root system into the shoot, allowing it to be photosynthetically active. In

the fall, those nutrients move back, thus autumn harvesting leaves the nutrients in the root for growth needs the following spring. It has been shown, in Denmark for example, that these crops can maintain a high level of productivity over as much as 20 years without application of nitrogen.

Two frontrunners in this arena are switchgrass, which has been heavily trialed by the USDA with much progress made, and miscanthus, which has been trialed quite extensively in Europe. The plant we work with⁴ is a hybrid (*Miscanthus x giganteus*) of *M. sinensis* and *M. sacchariflorus*. They have different ploidy levels, so the hybrid is a sterile triploid, eliminating the risk of it becoming invasive. The triploid is very productive. It is closely related to sugar cane and to sorghum. In our genomics work we are using sorghum as a scaffold for addressing the sequence of miscanthus. In 2002 we ran three trials in Illinois, planting rhizomes—rather like planting potatoes—of miscanthus and seeds of ‘Cave-in-Rock’ switchgrass, the recommended cultivar from Illinois. In 2004, the trial number was increased to seven. With BP’s help, we are now setting up trials around the country and in Canada.

MISCANTHUS

We say that by the fourth of July, corn should be knee high. Figure 1 shows that by that date in 2006, miscanthus was already high enough to hide me, demonstrating how much more efficient it is than corn in intercepting radiation early in the growing season. Even with poor conditions in the spring of 2008, miscanthus is already covering the ground (June 4), whereas some of our corn is only at the fourth leaf stage. By early August the crop is usually over 11 feet in height (Fig. 2) and by late October it is flowering (Fig. 3). The crop in Fig. 3 produced 26 tons of dry matter per acre, one of the highest yields we have seen. That was in 2004. January, when it has died back (Fig. 4), is a good time to harvest because the atmosphere is dry—you can get its moisture content down to 6 or 7%—and farm equipment is idle. We often harvest in February using the Animal Science Department’s cutting and baling equipment. Bales left in the field for as much as 2 years lost remarkably little biomass. Miscanthus is a traditional thatching material in Japan, which shows that it’s not easily broken down when exposed to the elements.

In plot trials around the state, we found that miscanthus consistently out-yielded switchgrass. It has been suggested that if we had included the cultivar ‘Alamo,’ we would have seen higher switchgrass yields and that may well be the case. However, published records show that miscanthus has been consistently more productive than switchgrass. The trials we are now setting up across the country should give us a better idea. But, in 2004, our best plots in south and central Illinois gave over 20 tons per acre. One of the reasons for this yield level is that miscanthus intercepts solar radiation for a longer period of the year than does corn (Fig. 5). It invests a considerable amount of biomass in the roots. Over 5 years, we have accumulated, on average, about 15 tons of dry matter—about 7 tons of carbon—below ground. The idea that planting something like this means you forego any opportunity to sequester carbon is certainly incorrect.

⁴<http://miscanthus.uiuc.edu/>



Figure 1. Miscanthus in Illinois: July 4.



Figure 2. Miscanthus in Illinois: early August.



Figure 3. Miscanthus in Illinois: late October.



Figure 4. Miscanthus in Illinois: January.

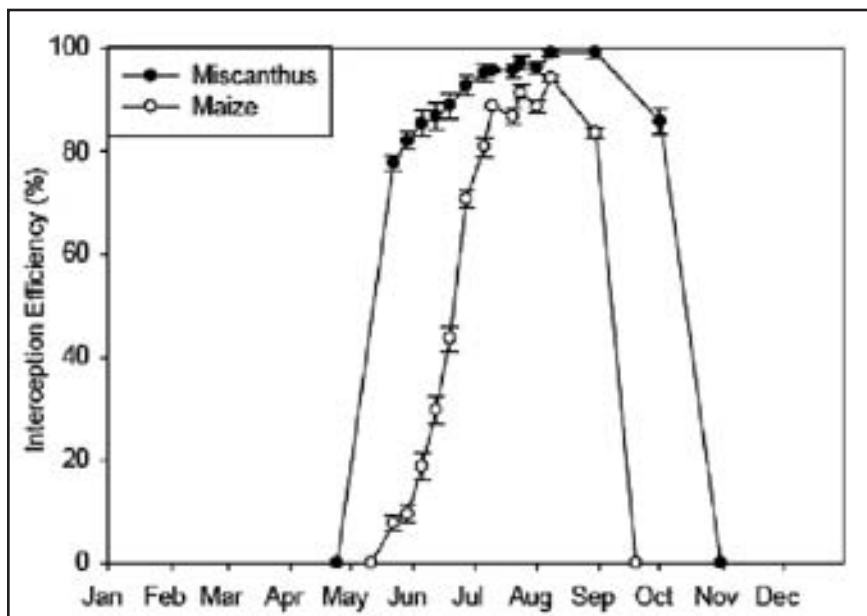


Figure 5. Light-interception efficiency, miscanthus and corn, 2007.

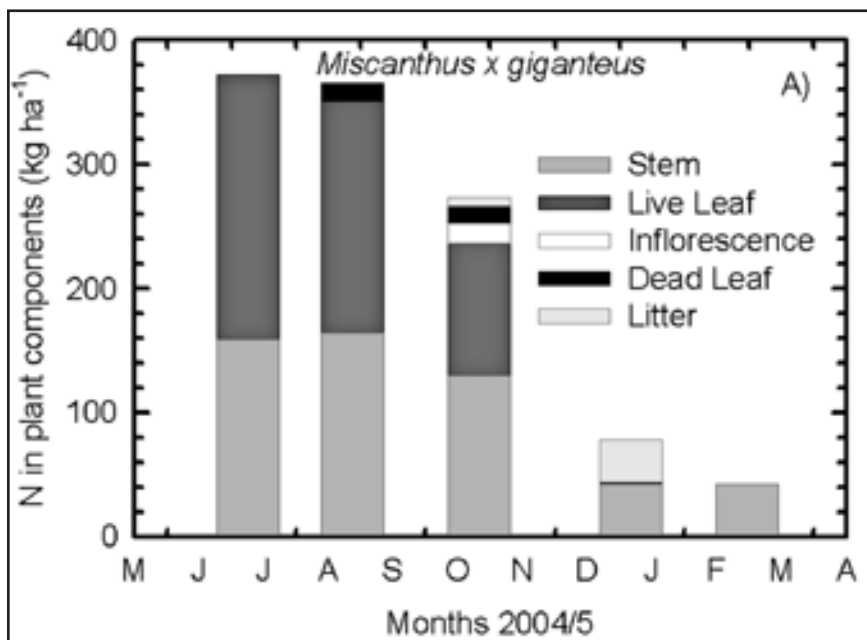


Figure 6. Miscanthus: shoot nitrogen distribution.

Miscanthus does require nitrogen; in one experiment the shoot accumulated almost 400 kg of nitrogen per hectare or 200 pounds per acre during the summer months (Fig. 6), but with the onset of autumn that material was translocated below ground and relatively little nitrogen was removed when the shoots were harvested in February.

IMPLICATIONS FOR FUEL PRODUCTION

What does this mean in terms of fuel? To achieve the “20 in 10” target of 35 billion gallons of ethanol, how much land would be needed? At current corn yields, it computes at 25% of row-crop land in the United States (Table 1). A yield of miscanthus of 15 tons per acre computes at about 8% of crop land. It was suggested at this meeting that 1,000 gallons of ethanol per acre from corn will be possible with improvements in seed yield and inclusion of the stover as a feedstock. But even with current yields of unimproved miscanthus and little knowledge of its optimum agronomy, we should be able to average 1,500 gallons per acre.

Another way of looking at this question is in terms of a need for about 23 million acres (Table 1), which is about the area now planted to corn for ethanol. If we planted miscanthus on that land we could achieve the long-term target without taking any further land out of food/feed production. Furthermore, we know from Europe that miscanthus can be grown on marginal land; in the west of Ireland, on shallow acid soils, low in fertility and never previously used for row crops, 10 tons of dry matter per acre were obtained.

*TABLE 1. LAND AREA REQUIRED FOR VARIOUS CROP OPTIONS
(HEATON ET AL., 2008).*

Feedstock	Harvestable	Ethanol	Acres needed for	Fraction of
	biomass		35 billion gals	2006 harvested
	(t/acre)	(gal/acre)	of ethanol	US crop land
			(millions)	(%)
Corn grain	4.5	454	70	24
Corn stover	3.0	330	106	37
Corn total	7.5	784	42	15
Prairie	1.7	169	207	73
Switchgrass	5.6	557	63	22
Miscanthus	15	1,500	23	8.0

WATER-USE EFFICIENCY

How water-use efficient is miscanthus? You can't get large amounts of biomass without water, but its water-use efficiency is equivalent to that of sorghum—for a kilogram of water it gives about 10 grams of biomass, with a vapor pressure deficit of 1 kilopascal (Illinois average)—so it's pretty good. A rainfall of 1,000 millimeters in Illinois allows a theoretical production, if the plant is capable of it, of 100 tons per hectare or about 40 tons per acre. In Nebraska, with about 500 millimeters and 4 kilopascals, the yield potential drops to about 12.5 tons per hectare or 5 tons per acre. Almost anywhere east

of the Mississippi River will have enough precipitation to produce 40-ton crops with the appropriate germplasm. In fact, the further east and south you go, the better are the conditions for miscanthus productivity.

MISCANTHUS IMPROVEMENT?

Switchgrass and miscanthus cover the ground for similar periods of time, so why does the latter produce more biomass? The reason is that miscanthus's photosynthetic rate is higher. This tells us that improved photosynthesis may be achieved in other crops. In the past 30 years, we've learned a lot about photosynthesis, little of which has been applied to crop plants because the information has not been viewed as particularly important. If anything, too much productivity has been seen as a problem, rather than too little. Furthermore, a huge range of other opportunities has been identified in recent decades that could be applied to agriculture. High yields are clearly important if biofuel crops are to be successful.

Our work to date has been with just one genotype of miscanthus. It is likely that superior alternatives exist. We need to look for higher leaf photosynthetic rates, better early-season growth, and ecotypes for various climate zones. The potassium level is relatively high which is an advantage if it can be translocated to the roots. Lower lignin content would be advantageous, as would ability to retranslocate labile lignocellulose.

EBI

Although we hear a lot about greenhouse-gas balance, it's actually never been measured for important crops. At EBI, we are comparing miscanthus, switchgrass, no-till continuous corn and mixed-grass prairie, looking at their exact greenhouse balances and nitrogen drainage patterns, side by side. One of the themes of the Institute is that all of the people who are funded—the postdocs and graduate students—work together. Environmentalists, genomicists, microbiologists and plant breeders are located in a building adjacent to the Morrow plots, which is probably the longest running experiment on sustainability in the United States.

REFERENCE

Heaton EA *et al.* (2008) Meeting US biofuel goals with less land: The potential of *Miscanthus*. *Global Change Biology* 14(9) 2000–2014.



STEPHEN LONG has a BS in agricultural botany from the University of Reading (UK) and a PhD from the University of Leeds. He was professor of environmental biology at the University of Essex, and has held appointments at Brookhaven National Laboratory, the Smithsonian Institution and the University of Vienna. He moved to the University of Illinois in 1999 to his present position:

Robert Emerson professor in plant biology and crop sciences.

Dr. Long is founding and chief editor of *Global Change Biology* and is listed by the Institute of Scientific Information as one of the 250 most highly cited authors in plant and animal biology, and one of the twenty most cited authors on global change. He has been a contributing author and referee for *Assessment Reports* on the scientific basis for climate change for the UN Intergovernmental Panel on Climate Change, and has served on several national and international committees for research on renewable energy and global change.

He is deputy director of the University of California-Berkeley and University of Illinois Energy Bioscience Institute—which was recently awarded \$500 million over 10 years by BP. He is a fellow of the American Academy for the Advancement of Science.