AMERICAN Scientist

97(5), Sep-Oct 2009, FEATURE ARTICLE

Taking Measure of Biofuel Limits

When pinning hopes on biofuels, an energy-hungry world must adapt to plant production capacities and resource limits

Thomas R. Sinclair

+ enlarge image

In a justified rush to cut fossil fuel consumption, some nations are embracing biofuels as a petroleum alternative at the gas pump. Using sugarcane, Brazil already produces 24.5 billion liters of ethanol a year to fuel car and truck engines. In the United States, annual ethanol production has reached 40 billion liters, or 10 billion gallons. The U.S. Energy Independence and Security Act calls for 144 billion liters of ethanol per year in the U.S. transportation fuel pool by 2022. That equals 25 percent of U.S. gasoline consumption today. No more than about 40 percent is to be produced with maize, an important food and export crop. Non-grain feedstock is supposed to supply the rest.

Before nations pin big hopes on biofuels, they must face some stark realities, however. Crop physiology research has documented multiple limits to plant production on Earth. To ramp up biofuel crop production, growers must adapt to those limits or find ways around them. Such advances may not be as simple as some predict. Plants and their evolutionary ancestors had hundreds of millions of years to optimize their biological machinery. If further improvements were easy, they would probably already exist.

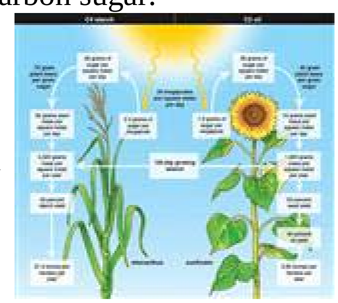
Fundamentally, creating ethanol from plant mass is harnessing solar energy derived from light absorbed by plants. Photons give plants the energy they need to fix carbon dioxide into all their organic compounds. Chlorophyll and other pigments absorb photons first to synthesize the basic organic building block $(CH_2O)_n$, from CO_2. All remaining plant compounds are synthesized from $(CH_2O)_n$: first simple sugars, then starch, cellulose, hemicellulose, oils, proteins, nucleic acids and the rest. Most ethanol production today starts with stalks of sugarcane or grain from maize, sources of sugar and starch that are easily fermented to create fuel.

In theory, a huge supply of plant sugars for ethanol could also one day come from the abundant cellulose and hemicellulose in tree trunks and the stems of grasses and other plants. But protein and lignin, the tough polymer that gives plants their structural strength, encapsulate cellulose and hemicellulose. Once isolated, the use of hemicellulose has the additional challenge of yielding five-carbon sugars that are not readily digested by existing fermentation microbes. Biotechnology researchers are working on new microbes to digest these five-carbon sugars, but such approaches are not yet commercial.

No matter what techniques are developed to expand biofuel feedstock, some basic physical and physiological limitations will still apply. Plants cannot be grown without three crucial resource inputs: light, water and nitrogen. Each of those inputs will be needed in substantial quantities, yet their availability in the field is limited. As important, so far plants make use of those resources only at established rates. In fact, the close relationship between the available amounts of these resources and the amount of plant mass they can produce—not human demand—will determine how much biofuel the world can produce.

Constraints with Light

Plants have evolved highly effective photosynthetic systems to collect and use light. Photosynthetic pigments in leaves absorb photons, causing a jump to a higher energetic state. This energy is used to fix CO_2 within a pathway that produces a three-carbon sugar.



+ enlarge image

Plant species such as wheat that rely exclusively on this pathway are referred to as C3 species. When no other resource shortages limit plant growth, there is an approximately linear relationship between the amount of light absorbed by a leaf canopy and its fixation of CO_2 to form plant mass. For C3 species, approximately 1.9 grams of sugar are produced for each megajoule (MJ) of solar energy intercepted by the leaf canopy. After hundreds of millions of years of evolution, these systems are highly efficient within the physical and thermodynamic constraints of photosynthesis and plant growth.

In other plants, a precursor biochemical pathway has evolved with a high affinity for CO_2, which expands their sugar production. The precursor pathway generates a four-carbon organic acid, so these species are identified as C4 species, which include sugarcane and maize. A small molecule bearing a carboxyl group (—CO2) moves to the vicinity of the carbon fixation enzyme in the leaf, and in a series of biochemical steps, CO_2 is released. This additional pathway concentrates CO_2 for photosynthesis and results in several important advantages under some conditions, including an increased production of up to 2.4 grams of sugar per MJ of solar energy intercepted by the leaf canopy.

Given these rates, the maximum production of plant material a crop field can produce can be readily estimated based on the solar energy reaching Earth’s surface. The first step is to calculate the plant mass that can be produced from sugar synthesized in photosynthesis. The amount of plant mass produced depends on the composition of the tissue: 1 gram of photosynthetic sugar, for instance, can yield about 0.83 gram of starch and cellulose, 0.40 gram of protein or 0.33 gram of lipid. For example, C4 species such as maize mainly produce carbohydrate materials. Those species produce 0.75 gram of plant mass per gram of sugar from photosynthesis, translating to about 1.8 grams of plant mass per MJ of intercepted solar energy. Rice and wheat are C3 species that also produce mainly carbohydrates, and their maximum yield is about 1.4 grams mass per

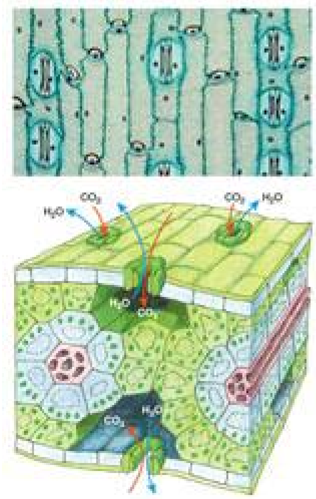
MJ of intercepted solar energy. Oil crops such as sunflower and peanut, potential biodiesel feedstocks easily extracted by simple squeezing, have a conversion of 0.42 gram of oil per gram of sugar. Their yield is only about 0.8 gram of mass per MJ of intercepted solar energy. These simple calculations show the superior yield potential of C4 species and why they are favored as potential biofuel feedstock.

Using the above estimates of mass productivity, it is possible to estimate the maximum daily production of various plant species. Assuming a very bright day in temperate areas, the daily intercepted solar energy may be 28 MJ per square meter. Therefore, the maximum daily production of a C4 grass species is 50.4 grams per square meter, and that of a C3 oil crop is 22.4 grams per square meter. Of course, the sky is not always cloud free during a growing season. Assuming that average daily solar energy is no more than 20 MJ per square meter, the average daily production is no more than 36 grams per square meter for C4 plants and 16 grams per square meter for C3 oil plants. If temperature and water availability are sufficient in temperate climates to allow four months, or 120 days, of full solar radiation interception, the maximum annual mass yield for a C4 grass would be 4,320 grams per square meter, or 43.2 metric tonnes per hectare. This yield estimate is in the range of maximum yield of sugarcane grown in the United States. For the seasonal lifespan of maize, there may be only the equivalent of 90 days of complete light interception. In addition, the harvested grain is only half the final plant mass. So the maximum annual grain yield for corn is estimated at 1,620 grams per square meter or 16.2 metric tonnes per hectare. This estimate is comparable to the highest current maize yields that have been obtained under ideal growing conditions. Maximum daily yield of a C3 oil crop is the lowest. Seeds from crops such as sunflower and peanuts have about 40 percent of their grain weight in oil. Therefore, the maximum oil yield is estimated to be 385 grams per square meter, or 3.85 metric tonnes per hectare, a yield that exceeds what most farm fields actually produce.

Maximum plant yield, it must be remembered, requires that all essential resources be abundant and that environmental constraints, including pests, be controlled. In the United States, for example, the national maize yield averages about 10 tonnes per hectare or 160 bushels per acre. Given that fermentation of one tonne of maize grain yields about 400 liters of ethanol, the U.S. goal for the year 2022 will require corn sown on an additional 15 million hectares. That equals 37 million acres, about half the U.S. land currently used to grow maize.

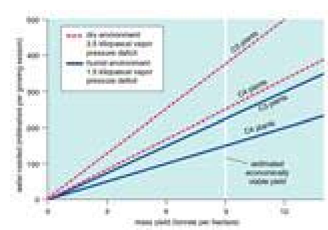
Estimating the land dimensions (or the light reception area) required for cellulose and hemicellulose ethanol feedstock is more difficult. Because viable means do not yet exist to use plant mass sources for those materials to make ethanol on a production scale, the precise production efficiency is unknown. It is reasonable to estimate, however, that one ton of dry plant mass can produce 200 liters of ethanol. That means the U.S. 2022 production goal of 86 billion liters from non-maize sources would require that 430 million tons of plant feedstock be produced annually. Samuel B. McLaughlin of the Oak Ridge National Laboratory and colleagues estimated in 2002 that a 9-tonnes-per-hectare average annual harvest was required for an economically viable ethanol industry based on C4 grass in the U.S. Hence, 48 million hectares, or 118 million acres, would be required to grow plant material for cellulose-based ethanol, with more land needed if yields were to prove smaller. Such land requirements are not trivial. That is 50 percent more than the area already under cultivation in the U.S. for any single crop: Maize and soybean fields total about 29 million hectares each and wheat totals 21 million hectares. If efficiencies in ethanol production from feedstock can be doubled, which is a goal, the land required would drop by half but would remain substantial. Since the most amenable land for high-yield crop production is already farmed, finding enough new acreage could pose a major challenge.

What About Water?



+ enlarge image Plant growth is directly related to water availability. Plants must draw substantial amounts of water from soil, in part to offset ongoing water vapor lost from their leaves. Tiny pores called stomata in the epidermis of leaves allow CO_2, which is vital to plant growth, to diffuse into leaves. But stomata also allow water vapor to escape—at rates that increase in dry, low-humidity environments. This physical intimacy between growth and water loss has been recognized for more than 300 years and is well enough understood to be expressed in the following equation: $T = G \times VPD / k$. *T* is transpiration (in grams per square meter), *G* is plant growth (also in grams per square meter), *VPD* is vapor pressure deficit measured in pascals, and *k* is an efficiency coefficient for each species, also in pascals.

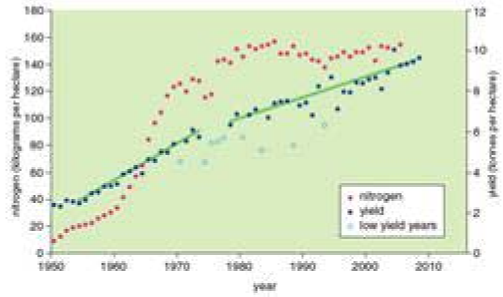
Understanding *VPD* is particularly important in calculating the amount of water lost by plants per unit of growth. The *VPD* is the difference between the saturated vapor pressure of the air inside leaves based on their temperature and the vapor pressure of the atmosphere. This difference in vapor pressure is the gradient that drives water loss. In climates with hot, dry atmospheres *VPD* is high, resulting in large amounts of water loss per unit of plant growth. The efficiency coefficient, *k*, is dependent on a number of variables. The two dominant ones are whether a plant depends on C3 or C4 photosynthesis and the biochemical composition of its plant material. The value of *k* is about 9 pascals for C4 grass, about 6 pascals for C3 grass and about 5 pascals for oil-producing C3 species. Under practical field conditions, the high photosynthetic capability of C4 species is a major advantage in producing substantially more plant mass per unit of water. Still, in environments with limited water supplies, mass production of any plant material is limited to the amount of water available to plants.



+ enlarge image With the transpiration equation, it's possible to calculate the amount of water needed for a crop plant species to be economically viable in a given setting. In a comparatively arid environment with an effective *VPD* of 2.5 kilopascals, usually associated with low rainfall, the water requirement is likely to be too great to allow C3 species production and would even pose a challenge for a C4 species at the estimated viable production threshold. Cellulose-based feedstock production is much more plausible in more humid areas (1.5 kilopascals *VPD*) for both C3 and C4 species at the 9-tonnes-per-hectare yield level. Of course, further increasing yield will require a proportional increase in the amount of water needed for transpiration.

In the case of ethanol production from grains, this equation must be adjusted since only about half the plant mass is harvested. Therefore, the water requirement must be doubled to achieve the same yield. For most crop production in the U.S., year-to-year variation in grain yield is closely tied to the amount of available water. Despite claims that crop yields will be substantially increased under water-limited conditions by the application of biotechnology, the physical linkage between growth and transpiration imposes a barrier that is not amenable to genetic alteration.

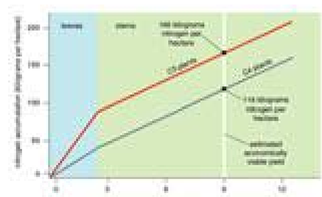
Don’t Forget Nitrogen



✚ enlarge image

Nitrogen is vital to all living things. It’s needed for the synthesis of fundamental building blocks: DNA, RNA and proteins. Although nitrogen (N_2) is abundant in Earth’s atmosphere, strong, triple covalent bonds make that supply inaccessible to plants and animals. Nitrogen is only accessible in less abundant ammonium (NH_4^+) or nitrate (NO_3^-). Even though plants have sizable nitrogen needs, biologically available nitrogen is often scarce in natural ecosystems. Shortages limit plant growth and biomass accumulation.

Considering the key role of nitrogen in plant production, it is not surprising that the rise and fall of human societies has been so closely linked to nitrogen availability for crops. Infertile lands helped unravel societies as disparate as those linked to the Roman Empire and Easter Island. Heavy application of nitrogen fertilizers, made with large amounts of natural gas, were key to yield increases that characterized the so-called Green Revolution during the mid-20th century. The use of nitrogen fertilizer per land unit stabilized in the U.S. about 1980 and, not surprisingly, the rate of maize yield increases slowed substantially at the same time from 170 kilograms per hectare per year (2.7 bushels per acre per year) to 100 kilograms per hectare per year (1.6 bushels per acre per year).



✚ enlarge image

An estimate of the total nitrogen required by plants to produce adequate plant mass can be calculated from the amount of nitrogen required in functional leaves and stems. First, it is necessary for plants to develop a large enough leaf canopy to maximize the interception of solar energy: 4 square meters of leaf area per square meter of soil surface area. To obtain maximum growth, nitrogen concentration in leaves of C4 plants needs to be about 1 gram per square meter of leaf area. Without the precursor pathway to trap CO_2, the concentration of the photosynthetic proteins must be substantially greater in C3 species to achieve high photosynthetic rates. In fact, C3 species under the current atmospheric CO_2 concentration cannot match the maximum photosynthetic rates of C4 species. For C3 species to obtain their maximum photosynthetic rates, leaf nitrogen concentration needs to be about 2.2 grams per square meter of leaf area. Therefore, the amount of nitrogen needed per unit of land area in leaves needed to sustain plant growth at a high rate is obtained by multiplying by the leaf-to-land ratio, which is 4. This results in an approximate nitrogen requirement of 4 grams per square meter of land for C4 species and 8.8 grams per square meter for C3 species.

Nitrogen is not only required in leaves. It is needed in stems and to produce structural strength in plant cell walls. Although the amount of nitrogen required in growing stems varies, a representative concentration is roughly 12 milligrams nitrogen per gram of stem. Such stem material is the primary source of cellulose and is the main variant accounting for differences in plant nitrogen requirement. For these calculations at low levels of available nitrogen, it is assumed that all plant mass is first assigned to leaves. After sufficient nitrogen is accumulated to meet leaf needs, further mass increases result in increasing amounts of stem mass, hence increasing the nitrogen requirement. As is the case with water, it's possible to calculate the threshold amount of nitrogen required to make a given crop economically feasible.

Fortunately, all the required nitrogen described above need not be replenished each year in crop fields. Rough estimates of the nitrogen balance for biofuel crop fields can be calculated by considering the various processes influencing what's known as the nitrogen budget. Plants grown annually for mass likely would be harvested each fall after growth was finished and plants were dried, from either their natural life cycle or a killing frost. Senescent leaves drop to the soil and can potentially contribute to the nitrogen store for the subsequent crop. Nitrogen removed from the fields would be contained in the stems, which commonly have a nitrogen concentration of approximately 5 grams N per kilogram of stem. Therefore, harvesting 9 tonnes per hectare removes about 45 kilograms N per hectare. Subtracting the amount of nitrogen removed from the field makes clear that, for the next crop, 73 kilograms and 121 kilograms per hectare of nitrogen will be required by C4 and C3 species, respectively.

Not all nitrogen remaining in a field, however, is available for a subsequent crop. In fact, nitrogen is notoriously ephemeral in cropping systems. Large losses result from runoff and leaching, which move nitrate and other nitrogen compounds into groundwater and surface waterways where they can be environmental hazards. In addition, microbes can denitrify nitrate—usually the common form of nitrogen in the soil—by producing oxides of nitrogen that are released into the atmosphere and contribute to greenhouse gas concentrations. The extent of these losses depends on a number of factors including the slope of a field, soil surface conditions, soil characteristics, frequency and intensity of rains, water content, and air temperature.

Even under optimal cropping management, plants usually take up less than 60 percent of applied fertilizer, and uptake often may be 40 percent or less. Losses of nitrogen from crop residue may be greater, especially when soil surfaces are exposed during heavy winter precipitation. Assuming a 40 percent recovery of nitrogen from a previous crop, nitrogen remaining in a field for the subsequent crop may be only about 29 kilograms per hectare for C4 species and 48 kilograms per hectare for C3 species. Nitrogen input from thunderstorms and free-living fixers of atmospheric N_2 contribute some usable nitrogen to soil, but usually no more than about 30 to 40 kilograms N per hectare. Assuming 35 kilograms N per hectare per year from natural inputs, that combined with residual nitrogen from the previous year produces nitrogen levels of approximately 64 and 83 kilograms per hectare for C4 and C3 species, respectively. Those levels leave a nitrogen deficit of roughly 54 kilograms per hectare for C4 species and 83 kilograms per hectare for C3 species. So a question arises: How can this deficiency be resolved in biofuel feedstock crops?

Maintaining Adequate Nitrogen

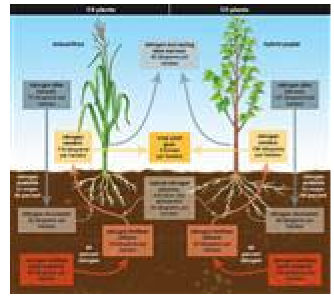
Mineralization of organic matter can be an important source of nitrogen in soil. Microbes break down organic matter in soil and release nitrogen into that soil. The mineralization rate depends on a number of factors, including the organic content of the soil, temperature and water availability. Organic matter in soils can vary widely from virtually none in sandy soils to 90 percent in peat soils. Most lands suitable for growing plants for biofuel will likely have about 10 to 40 grams per kilogram of organic matter near the surface. For the crop with a nitrogen budget deficit of 54 kilograms per hectare per year and a 60 percent recovery of mineralized nitrogen, the biofuel crop will need 90 kilograms of N per hectare derived from mineralization of soil organic matter. The annual withdrawal of this amount of nitrogen in soil is equivalent to a loss of roughly 0.25 gram of organic matter per kilogram each year. Although this decrease rate is usually small when compared to all the original organic matter in the soil, a cropping practice dependent on a continuous withdrawal clearly is not sustainable.

That gives reason to question experiments on miscanthus, the perennial grass considered a potential cellulosic ethanol feedstock candidate. The studies showed no observed response to nitrogen fertilizer. But those results indicate that initial release rates of nitrogen from soil mineralization may be adequate only for the first stages of biofuel cropping. They do not suggest that long-term soil “mining” is sustainable for biofuel crop production. Nitrogen fertilizer of annual biofuel crops will inevitably be needed once soil organic matter decreases to levels limiting plant growth. A study of the history of the exploitation of soil organic matter in the Pampas of Argentina in the first half of the 20th century reveals the importance of protecting organic matter in soil. Expectations for cellulosic yields are sometimes double and triple the 9-tonne-per-hectare yield used in the above estimates. If such high yields are to be achieved, the need for nitrogen inputs will be much greater.

One solution often offered to overcome nitrogen deficits is to grow perennial plants that can transfer and store nitrogen in their rhizomes and roots between crops. Unfortunately, very little research has been done exploring nitrogen redistribution within C4 grass plants. The very few studies that report seasonal changes in the amount of nitrogen stored in tissue below-ground do not seem to show close synchrony with changes in the nitrogen accumulation in tissue above ground. Substantial research will be required to develop plants with an over-wintering storage capability in below ground tissue.

As with cellulose harvests, harvesting grains takes substantial amounts of nitrogen from fields. For example, maize grain contains about 13 grams N per kilogram and wheat grain about 22 grams N per kilogram. If the grain yield of these crops is in the range of 10,000 kilograms per hectare, or 10 tonnes per hectare, then 130 and 220 kilograms N per hectare are removed from the field by the harvest of maize and wheat, respectively. Again, these substantial amounts of nitrogen must be replenished to a large extent by adding nitrogen fertilizer.

+ enlarge image



Light, water and nitrogen will be essential for growing biofuel feedstocks. As shown in the above analyses, the availability of these resources will be critical to achieving ethanol production goals set by the U.S. Energy and Security Act. Even if the current increase in maize yield can be sustained at 0.1 tonne per hectare per year, the equivalent of 40 percent of today's U.S. maize crop will be required for ethanol production while other domestic and export demands for maize also must be met. Identifying land area for cellulosic plant production will be even more challenging. Depending on the efficiency of ethanol production from cellulosic feedstock, somewhere between 25 and 50 million hectares of new land must be brought into high and sustainable agricultural production to achieve the required yields. Since this land-use conversion would need to take place roughly over a decade, it would be the most extensive and rapid land transformation in U.S. history.

To complicate matters, land used for cellulosic feedstock must be in regions with sufficient rainfall to achieve needed yields. The amount of water transpired by those crops could be large enough to influence the hydrologic balance of farming regions. An unanswered question is whether stream and aquifer flows from these areas would also remain adequate to meet all local freshwater needs. Finally, increased nitrogen supplementation required for the new crops will result in more nitrogen leaching into natural waterways and more greenhouse gas released into the atmosphere, introducing real management and environmental challenges. While biofuels can be a contributor to the energy needs of the future, realistic assessments of the production challenges and costs ahead impose major limits.

Bibliography

- Boehmnel, C., I. Lewandowski and W. Claupein. 2008. Comparing annual and perennial energy cropping systems with different management intensities. *Agricultural Systems* 96:224–236.
- Mclaughlin, S. B., et al. 2002. High-value renewable energy from prairie grasses. *Environmental Science and Technology* 36:2122–2129.
- Penning de Vries, F. W. T. 1975. Use of assimilates in higher plants. In *Photosynthesis and Productivity in Different Environments,* J. P. Cooper ed. London: Cambridge University Press.
- Sinclair, T. R., and L. C. Purcell. 2005. Is a physiological perspective relevant in a 'genocentric' age*? Journal of Experimental Botany* 56:2777–2782.
- Sinclair, T. R., L. C. Purcell and C. H. Sneller. 2004. Crop transformation and the challenge to increase yield potential. *Trends in Plant Science* 9:70–75.
- Sinclair, T. R., and R. C. Muchow. 1999. Radiation use efficiency. *Advances in Agronomy* 65:215–265.
- Sinclair, T. R., and T. Horie. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. *Crop Science* 29:90–98.
- Sinclair, T. R., C. B. Tanner, and J. M. Bennett. 1984. Water-use efficiency in crop production. *BioScience* 34:123–127.