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Agronomic Potential for Biomass Production

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Abstract

Plant biomass may be an economic means of harvesting and storing solar energy. Present day agricultural practices, however, do not allow maximum biomass production in the primary sense, or as crop residue. Biomass production is closely related to photosynthetic potential of single leaves in a complete canopy. New developments in crop selection and culture may allow more efficient canopies and photosynthetic rates. Genetic improvement in vegetative growth as well as grain or economic product would increase production potential for both fuel crops and crop residues. Long range agronomic considerations on soil structure and land use would also need to be considered.

1. INTRODUCTION

Plant matter that consists of 90-95% organic compounds has been used for biological production of methane (10). In this manner plant biomass is utilized as an energy storage form and then converted to a utilizable form such as methane (31). At present, the main economic sources of plant matter are from crop residues and from by-products of agricultural and forestry enterprises. Economic assessment of this process of energy generation from crop residues has been marginally favorable (9). Alternative to crop residues is the concept of "fuel crops", or crops grown specifically for bioconversion to methane or other suitable energy forms. Unfortunately, there is little agronomic data to give good estimates of production when biomass is the primary objective. That possibility, along with use of crop residues, is the subject of this paper.

2. CHARACTERIZATION OF CROP PLANTS

Since man's evolvement from a nomadic harvester to an activator in a society dependent on crop culture, plant agriculture has been of importance. This change in emphasis was predicated by man's requirement for food. Traditionally throughout history, food and fiber have been the predominant purpose for growing crops. Thus, genetic improvements in crop plants from simple selection by our ancestors to sophisticated techniques of modern-day plant breeders have been for food purposes. Cultural changes in history have also been oriented toward improved food and fiber production and quality.

Today there is a renewed interest in biomass production, but since few crop plants are managed for total production, cropping systems have some serious limitations. Present-day varieties of crop species have been heavily influenced by factors unrelated to primary production potential. Food, feed, and fiber preferences and secondary constraints such as pests, ease of culture, and need for diversity in operations have established priorities which frequently override biological efficiency. These limitations are obvious in corn where normal plant populations of 16-20,000 plants/acre are planted in rows for maximum grain production, in contrast to much higher populations planted in solid stands to achieve optimum biomass production (19). Further, modern corn hybrids have been selected for short stature and reduced vegetative growth (21) so that more of the dry weight above ground is located in the grain. Wheat and other small grains have had the same trend because of the desired increased grain yield and lodging (falling over) resistance of shorter plants.

Even forage species, where the entire topgrowth is harvested, have suffered in biological efficiency. Genetic and cultural selection have emphasized forage quality which often correlates poorly with high quantity. Further, due to economic characters, crops are often grown outside of their natural area of adaptation, another factor that lowers potential biomass productivity.

3. POTENTIAL PRODUCTIVITY

Agricultural systems are really photosynthetic systems, and hence can be assessed by their ability to convert solar radiation into a product of utility. This means that attention needs to be directed toward an understanding of the photosynthetic process in terms of light interception and utilization and in the distribution of the energy fixed into a form that is utilizable and harvestable.

Intensive agriculture is practiced on a very limited scale with reference to the total land mass of the earth. Intensive agriculture would be defined as a system where limitations such as water, fertilizer, weeds, insects, diseases, and plant density are not limiting productivity. It is readily apparent that it is not economically feasible to control all of these factors, but if they could, solar radiation, temperature (heat), and CO_2 would be the subsequent limiting factors to crop growth.

Three major mechanisms occur among plants for photosynthetic CO_2 fixation (37). Few crop plants fix CO_2 via the crassulacean acid metabolism system which is least efficient. Most warm-season crop plants like corn, sugar cane, and sorghum use the C_4 mechanism of CO_2 capture and pumping to the fixation site. This system is most efficient in terms of light use. Photosynthetically, these plants do not become light saturated even at full sun (Figure 1), and fix CO_2 at maximum rates of 40-60 mg CO_2/dm^2 leaf area/hour (17). In contrast, C_3 plants which rely largely on diffusion of CO_2 to the active site, reach light saturation at about 50% of full sun, and have maximum fixation rates of 20-30 mg CO_2/dm^2/leaf area/hour. Representative species include wheat, tall fescue, orchardgrass, alfalfa, soybeans and cotton. A major factor in the reduced efficiency of C_3 is the process of photorespiration which "drains off" about 50% of the potential fixation of C_3

species (24,37,38).

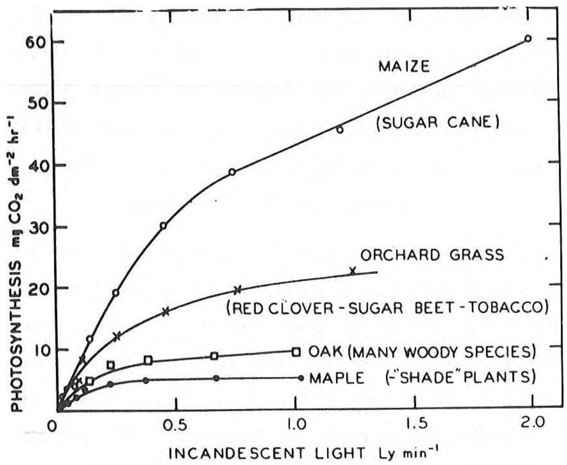

Figure 1. Photosynthetic responses of crop plants to radiation intensity (23).

Zelitch (37) compared agricultural productivity of above ground biomass and found that C_3 species were generally less than 50% as productive as C_4 when each was grown in its area of adaptation. Deciduous trees are almost all C_3 photosynthetic types (Figure 1) and have rates of 6-12 mg CO_2/dm^2 leaf area/hour.

Table 1. Average growth rate of several crop species. Data are 1969 U.S.D.A. agricultural statistics as cited by Zelitch (37).

Crop	Dry Wgt (lbs/A)	Growing season (weeks)	Growth rate $g/m^2/day$
C_4 species			
Corn Silage	7,080	17	6.7
Sorghum Silage	6,480	17	6.1
Sugarcane (cane)	16,200	36	7.1
C_3 species			
Spinach	580	5	1.9
Tobacco (Leaf & stem)	3,140	14	3.6
Hay (general)	3,600	20	2.9

Loomis and Williams (18) estimated canopy photosynthetic potential of corn (a C_4) species), corrected it for respiration, and concluded that the theoretical maximum crop growth rate would be 77 $g/m^2/day$ with 500 cal/cm^2 day of radiation. This corresponded to an efficiency of 12% for conversion of total radiation. This value is well above the 1-3% normally achieved in crop agriculture (21).

4. ACTUAL PRODUCTIVITY

The constraints of genetic selection and culture for specific purposes mentioned above do not allow agricultural crops to achieve their biomass potential. For example, in Missouri crop performance tests (22) grain yield of adapted corn hybrids grown at several locations averaged about 105 bushels/acre for 3 years across several locations without irrigation. Assuming the grain is equal to about 45% of the total above ground biomass (15) this calculates to an average growth rate of 9.2 g/m^2 day for the growing period. With irrigation, yield was 154 bushels/acre for 3 years at two locations. This corresponded to 14.4 g/dm^2/ day which is well below the theoretical maximum of 77 $g/dm^2/day$. Williams, Loomis, and Lepley (36) attempted to determine reasons for the difference between theoretical and actual productivity. Corn plants were grown at Davis, California, with adequate water, fertilizer, and weed control. Plant density was altered over a broad range from below the 16-20,000 plants/acre commonly used, up to 283,000 plants/acre. They found that crop growth rate was a direct function of the proportion of solar energy intercepted, and reached 52 $g/m^2/day$ for the highest population. Inability to harvest a high proportion of radiation for a long period of time was considered the largest limitation. Tanner and Peterson (34) have reported that 26 to 44% of the radiation incipient on a corn crop is transmitted (wasted) with 16,000 plants/acre depending on the row width. Corn is not grown commercially at high densities because it does not form an ear (21).

Leaf area required to intercept all the radiation varies with crop species (Figure 2). Most crops such as clovers and soybeans with predominantly horizontal leaves intercept all the radiation at leaf area index (LAI, leaf area/ground area) values of 4 to 5. In contrast grasses with more vertical leaves often need to reach LAI values of 10 to 12 before all the radiation is absorbed. In normal production corn has an LAI of 3.5 to 4.5 while total radiation interception occurs with an LAI of 12 (36).

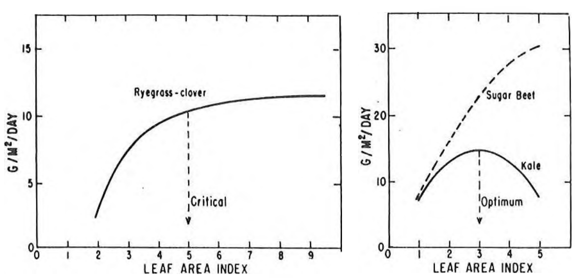

Figure 2. Crop growth rate response to variations in leaf area index (LAI, leaf area/ground area). Some crops have an optimum LAI because lower leaves are parasitic when shaded. Critical LAI (where 95% of light is intercepted) is greater than 5 for sugar beet (18).

Although forage grasses also need high LAI values to intercept all the radiation, they often do not achieve these high values because they are in a regrowing stage, or are harvested before the high LAI values are attained in order to obtain a higher quality forage. These data further illustrate that conventional agricultural hybrids and production practices do not allow maximum efficiency for biomass production. A few crops have an optimum LAI (Figure 2) because the lower leaves become "parasitic" when they receive low radiation. These plants would be poor producers of large amounts of biomass.

Since solar energy is the driving force for biomass production it seems most likely that high rates of production would occur with densely planted crops. In tropical environments sugar cane (a C_4 crop) maintained a growth rate of 37 g/m^2/day, a dense stand of cattail (a uniquely efficient C_3 plant) achieved 53 g/m^2/day, bulrush millet (a C_4 forage) has achieved 54 g/m^2/day) and sudan grass (another C_4 forage) has grown at 51 g/m^2/day (36). Growth rates for cool-season crops rarely approach these levels (11) even with a complete canopy of leaves because of their less efficient photosynthetic systems.

It is evident from the above discussion that high biomass production will occur when a dense canopy is associated with a high leaf photosynthetic potential. However, under most conditions the soil and aerial environment will also affect the energy conversion and growth process. This is especially true if these maximum rates are compared to what one might achieve on Missouri farms.

5. CLIMATE AND SOIL FACTORS

Climatic factors. Temperature, rainfall, and solar radiation are the dominant environmental factors that affect productivity in continental climates. Temperature interacts with crop growth through both the air temperature influences on a day-to-day basis and in dictating the length of the growing season. Solar radiation tends to be rather inflexible, except for variable cloud cover, with maximum intensity and daily duration occurring in June in northern latitudes. Minimum radiation in Missouri occurs during December and January when most crop species are winter dormant.

Cool-season crop plants (C_3 photosynthesis) grow very little at average daily temperatures below 4° C (39° F), reach maximum growth rates at average temperatures of about 20° C (68° F), and nearly stop growth at 30° C (86° F). In contrast warm-season crop plants (C_4 photosynthesis) grow little at average temperatures below 10° C (50° F), have maximum growth rates at about 30° C (86° F) and do not cease growth until average temperatures reach about 38° C (100° F). These temperature characteristics influence crop selection, planting date, and varietal maturity for a given growing season.

In Missouri, the growing season for cool-season crops is from about March 15 until November 1, with the summer temperatures during late June to mid-August being above optimum (14). This gives two periods of high production for crops such as forage grasses, one in spring after the canopy is developed and again in fall when temperatures reapproach the optimum. Growth is usually more than twice as rapid in spring as in fall because the days are longer to give more radiation, and the stems and seed heads are formed.

The growing season for warm-season crops is from about May 1 until October 1, with maximum growth rate occurring in July and August if water is available. These crops often do not develop a canopy early enough to take good advantage of the long days and high radiation of June, but this is largely due to the fact they are annuals and are planted later in the spring. The only warm-season perennials grown in Missouri are some range grasses and Johnsongrass. Because they do not need to be planted in spring they often make good growth earlier than warm-season annuals.

Even though cool-season species (C_3 photosynthesis) have a lower daily rate of production, they can offset some of the disadvantage through their longer growing season. In Missouri corn often produces 7 (non-irrigated) to 10 (irrigated) tons/acre of above ground biomass, while alfalfa may produce 6 and forage grasses 5 tons/acre annually with good management. Trees also take advantage of a long growing season to offset their slow photosynthetic rate, but still have low levels of biomass production in natural canopies (27).

Rainfall varies on an annual basis from about 36 inches in Northwest Missouri to about 50 inches in Southeast Missouri (13). However, during the May through September periods when temperatures are most suitable for rapid crop growth, average rainfall in Northwest Missouri is about 21 inches and in Southeast Missouri is only about 18 inches. Most intensive cropping systems in Missouri can effectively use more water than naturally provided during the growing season because of the high evaporative demand.

Figure 3 shows the relationship between rainfall and evapotranspiration for Columbia, Missouri. A deficiency during summer occurs in all of Missouri, to a

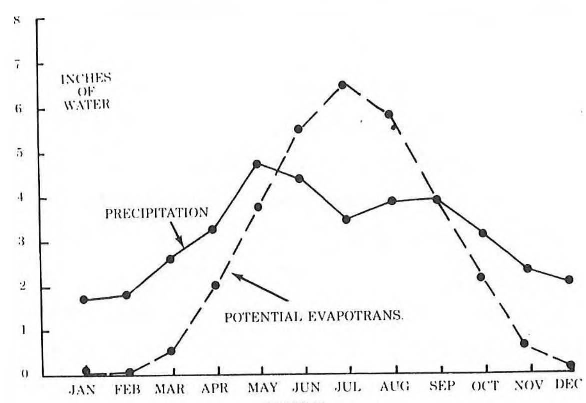

Figure 3. Potential evapotranspiration and rainfall during the year at Columbia, Missouri (30).

lesser degree in the Northwest and to a greater degree in the Southeast. During the period when rainfall does meet demand needs, plants withdraw water from the available supply in the soil. When the soil supply is not adequate irrigation becomes practical.

Soil factors. Sufficient evidence is available (8) to show that supplemental fertilization or addition of legumes is economic to production of agronomic yield. Providing mineral nutrients are supplemented to the soil in proper quantities, aeration and water holding capacity become the dominant factors affecting producivity (28).

Soil aeration is probably most closely related to internal drainage characters of the soil (30). Figure 4 illustrates the relationship between the two for potential productivity of summer annuals. The relationship is similar, but with somewhat different slopes and intercepts for cool-season annuals and perennials.

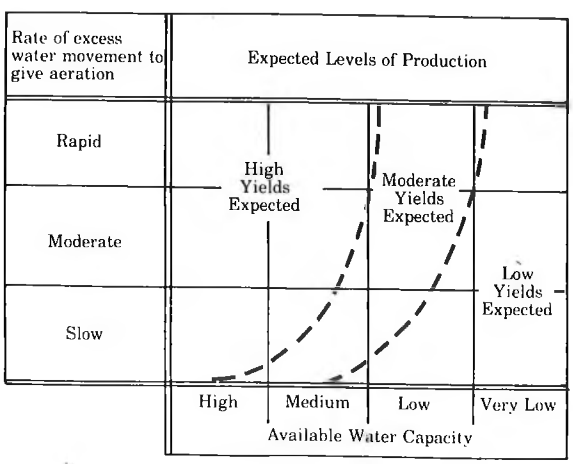

Figure 4. A guide for assessing the role of excess water movement and water holding capacity of soils on potential productivity of summer annuals (30).

Poor internal drainage is a characteristic of many Missouri soils. This causes excess water to be held in the soil during periods when rainfall exceeds evapotranspiration in spring and fall (Figure 3). Lack of aeration inhibits root growth and mineral uptake, and also leads to more disease problems for the plants.

High available water holding capacity (Figure 4) helps during summer when rainfall is less than evapotranspiration (Figure 3). During this period plants gradually deplete the stored water reserve which will be recharged again in fall. Most Missouri soils, and particularly those without a high water table, cannot adequately meet water needs during summer when evaporation demand is high, and hence the generalized response to irrigation (22).

Most soils in the "High yields expected" area of Figure 4 are already in intensive grain production. Those of "low yield expected" are usually in grassland, and those of "moderate yields expected" oscillate back and forth depending on economics. Scrivner (29) has proposed a method of evaluating soils for productivity by developing an index using several mineral and water characteristics. His report shows good linear relationships between soil productivity index and yields of alfalfa, wheat and corn.

It appears that economic production of fuel crops over the long term will be concentrated onto the extremes of soil type. On the best soils fuel crops could be intensively grown if made competitive economically with other crops. On lower index soils fuel crops would have less economic competition, and extensive use as an alternative to, or in association with pasture may be feasible.

6. CROPPING SYSTEMS

For maximum biomass production cropping systems are needed that allow interception and utilization of a high proportion of photosynthetic radiation during the entire growing season (11). Common agricultural practice does not allow for this as most plants are grown in monoculture, and only for the interval of the growing season for which they are best adapted (19.) This may mean that double cropping (producing two crops per year in sequence) may be the best alternative. Recently there have been a lot of reports(e.g. 25) suggesting that corn of soybeans planted after winter wheat or barley produces the same with or without conventional tillage between crops. Lack of tillage speeds transfer from one crop to another, and saves soil moisture by decreasing evaporation during the deficit portion of the growing season. Double cropping increases crop residue production, but the residue of the first crop is an important component as a mulch in summer that may limit its energy production value.

Fuel crop production under intensive management would not be limited to conventional agricultural practices. One disadvantage of present day double cropping is that the small grain crop needs to mature before it is harvested and the next crop planted. Nearly all of the biomass is produced earlier, but the seeds must dry. Early harvest would not be a problem in fuel crop situations, which would allow earlier planting of corn to achieve a canopy earlier, and a greater yield of biomass in that operation also. Small grains can be seeded in standing corn to begin development of a vegetative canopy before the corn crop is harvested. Using double cropping with present varieties could increase biomass over corn alone by 20-35% per season.

Another unconventional system is intercropping (12). In this system two crops that are not highly competitive to each other are grown together. Because each has its own particular environmental niche (e.g. optimum temperature, radiation usage, mineral requirements) first one crop and then the other makes maximum use of the environment. This allows the combination to produce more product/acre than either grown alone (Table 2). The main problem for conventional agriculture would be harvesting each individual in a mixture such as corn and soybeans. This would not limit use for biomass production where the individual product is not critical.

Table 2. Land use efficiency of growing mixtures as compared to summer productivity of each growing alone (12).

Crop mixture	Efficiency (%)	Location
Corn and rice	160	Phillipines
Corn and peanuts	150	Taiwan
Sorghum and cotton	150	Oklahoma
Corn and dry beans	140	Colombia
Corn and soybeans	140	India
Corn and sugarbeets	140	Canada
Sorghum and cowpeas	130	Nigeria
Corn and soybeans	120	Minnesota

Advantages of intercropping for fuel use, like as above or in forage mixtures, may be that the quality (C:N ratio) of the product for energy use could be manipulated to be more satisfactory than either component alone. Reports (12), of fewer insect problems in cotton when it was grown with sorghum are also an advantage of intercropping. Many systems have not been tested. Further, almost all systems tested have been on field crops. Weeds can also be very high producers of biomass and many of the most competitive weeds are C_4 photosynthesis plants (6).

7. USE OF FUEL CROPS

For fuel crop production the most economic means may be to use mixtures of perennial weeds, grasses, and legumes. New varieties of perennial C_4 grasses such as switchgrass and Caucasian bluestem have potentials to produce over 4 tons/acre by July 1 in Southwest Missouri (2). Regrowth during summer when moisture is low without irrigation can approach an additional 1 ton/acre. Seeding a cool-season legume with these species allows nitrogen fixation, extends the growing season (20) and may add additional biomass for the season.

Interseeding winter annual crops such as winter rye into perennial warm-season crops such as Johnsongrass or Caucasian bluestem may offer good biomass potential. Such a mixture may further benefit by also having a perennial legume included to provide some nitrogen. This mixture would likely have to be harvested at least three times in order to achieve maximum biomass production. These perennial mixtures would appear particularly desirable where slopes and soil condition could lead to erosion problems.

Without the contraints of having to harvest a crop for its economic product, or at a given age or stage of maturity to maintain quality, these mixtures and combinations could likely increase biomass production over conventional agricultural practices by 50 to 100%. These values would still be considerably below the theoretical maximum (18) and may be further improved by breeding and management. It is likely that due to climate and soil conditions in Missouri one could not achieve the theoretical maximum based on solar radiation.

Steffgen (33) suggests that as a fuel crop it is quite possible that rank growing plants, unlike our present crops, would be more efficient. Young forest plantations, after developing a complete canopy cover, can be as efficient as agricultural crops (26).

8. USE OF CROP RESIDUES

An alternative to fuel crops would be the use of crop residues and by-products from conventional agriculture (33). If this were to be feasible, "dual purpose" crops could probably be genetically developed. Corn may be a good example in that plant breeders have knowingly selected for less vegetative production and short stature. Grain sorghum is another example where the vegetative growth has been dwarfed. Normal counterparts could be redeveloped if the need was there to serve both grain and residue purposes.

A major disadvantage with removal of crop residues from the field is the long term effect on soil structure, and its implications for internal drainage and water storage in the soil. Mineral nutrients would also have to be restored. Baldwin (5) reports that soil conditions need to be carefully evaluated before deciding to remove crop residues. Many fine-textured soils as in Missouri uplands are subject to compaction and loss of aeration when crop residues are not returned. Coarse textured soils often have low organic matter content and would also benefit by having the residue returned.

Clausen and Gaddy (9) have described a methane generation system that incorporates the solid waste from plant biomass back to the soil. That system would recycle a high proportion of the mineral nutrients as well as the undigested organic material back to the soil. Whether or not this organic material is sufficient to offset the detrimental effects of total crop removal needs verification. Perennial crops usually do not suffer from total topgrowth removal. This occurs because the root system is very extensive and it is turning over annually to resupply the soil with organic matter. For this reason perennial crops have an apparent long term advantage.

9. CONCLUSIONS

Improvement in biomass production from both fuel crops and crop residues is certainly agronomically feasible. Present day varieties of crops and management practices do not exploit the potential of crop plants for biomass potential as either fuel crops or producers of crop residues. Photosynthesis rate is genetically controlled (4,37) and can be improved by plant breeding. Chemical methods may also be available (38) for decreasing photorespiration and dark respiration of some species to effectively increase photosynthetic potential.

While it has been known for a long time that legumes are able to fix atmospheric nitrogen to a utilizable form, it has only been recently that similar systems have been identified in certain warm-season grasses (35). More recently researchers in Florida (32) and Wisconsin (1) have shown other grasses including corn have nitrogen fixing ability when grown with certain microorganisms. Advances in nitrogen fixation would greatly lower the energy input (16) into crop culture, and could change dramatically the economics of food and fuel crop production.

Although it is a lot more remote at present, studies of the biological and agronomic mechanisms of solar energy capture may allow synthetic crop surfaces to be developed (7). These systems could fix sugars to be later incorporated biologically to high energy fuel carbon sources. Alternatively the electron transport portion of the photosynthetic system could be utilized for generating electricity directly (3). Simulated systems to date have had low output, but the concept needs to be explored.

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