NON–WOODY LAND PLANTS

AS A RENEWABLE ENERGY SOURCE

PRESENTED TO THE ACS SYMPOSIUM

BIOMASS AS A NONFOSSIL FUEL SOURCE

HONOLULU, HAWAII, 1979

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Contributed By.

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Table Of Contents

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INTRODUCTION

1. <u>Non-Woody Land Plants in Perspective</u>:

Literally thousands of terrestrial plant species can be regarded as potential energy sources. A majority of these are herbaceous seed plants which complete their growth and reproductive processes within a single growing season of a few months duration. They are widely distributed from arctic regions to the tropics (<u>1</u>,<u>2</u>,<u>3</u>). They are equally diverse with respect to their growth and anatomical characteristics, their cultural requirements, and their physiological and biochemical processes (<u>2</u>-<u>9</u>). Yet all have the capacity to convert sunlight to chemical energy and to store this energy in the form of biomass. An oven-dry ton of herbaceous biomass represents about 15×10^6 BTU's of stored energy. The direct firing of one such ton, in a stoker furnace with high-pressure boiler having a 70% conversion efficiency, would displace about two barrels of fuel oil.

In addition to their fibrous tissues, some species also produce sugar and starch in sufficient quantities to warrant extraction and conversion to

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ethanol. The latter can displace petroleum in the production of motor fuel or chemical feedstocks (10-19). Other species store additional energy in the form of natural hydrocarbons (20,21,22).

While it is not correct to say that herbaceous land plants have been over-looked as a domestic energy resource, only a small number have been examined closely for this purpose. Among the latter are tropical grass species of Zea, Sorghum, Saccharum, and Pennisetum which were recognized for their high yields of fiber and fermentable solids long before the oil embargo of 1973. Through-out their history as cultivated crops, plants such as corn, sweet sorghum, sugarcane, and napier grass have evolved extensive technologies for their cultivation, harvest, post-harvest transport and storage and for their processing and marketing. Yet, even for these plants major changes must be made in their management if they are to serve most effectively as energy crops (6,5,23,24). Other tropical plants having very fine botanical or agronomic attributes and enjoying a year-round climate suited to biomass production have been generally ignored as energy resources. Pineapple, cassava, and a range of underutilized tropical species are appropriate examples (4,8,13).

A majority of herbaceous land plants have never been cultivated for food or fiber. In warm climates wild grasses such as Sorghum halepense (Johnson grass), Arundo donax (Japanese cane), and Bambusa species are borderline cases where occasional use has been made of their high productivity of dry matter. In cooler climates self-seeding plants such as reed canary grass, cattail, wild oats, and orchard grass may be viewed with mixed feeling by landowners unable to cultivate more valuable food or forage crops. Plants such as rag-weed, redroot pigweed, and lambsquarters are recognized for their persistent growth habits while otherwise regarded as common pests. However, the value

of such species could rise dramatically as biomass assumes its future role as a non-fossil domestic energy resource.

2. <u>Prior Studies on Herbaceous Plants as Energy Sources</u>:

Aside from sugarcane and "allied" tropical grasses (6,7,13,23,24,25), relatively little attention has been given to herbaceous land plants specifically as sources of fuels and chemical feedstocks. Studies were initiated recently at Battelle-Columbus Laboratories on common grasses and weeds as potential substitutes for fossil energy (26). Plants showing promise as boiler fuels include perennial ryegrass, reed canarygrass, sudangrass, orchardgrass, bromegrass, kentucky 31 fescue, lambsquarters, and others. A range of species have indicated some potential as sources of oil, fats, protein, dyes, alkaloids, and rubber. Such plants include giant ragweed, alfalfa, jimsonweed, crambe, redroot pigweed, dogban, milkweed, and pokeweed.

In 1978 the US Department of Energy issued an RFP for herbaceous plant screening as a means to close the information gap in this area of biomass energy development (27). The DOE objective has two phases: First, to identify promising species for whole-plant biomass production in at least six different regions of the U.S., and second, to perform field evaluations on at least 20 species per region, with a view toward identifying those most suitable for cropping on terrestrial energy plantations. Arthur D. Little, Inc., was selected to conduct Phase I (2).

Six regions were designated on the basis of climatic characteristics, land availability, and land resource data provided by the U.S. Soil Conservation Service (2). A list of 280 potential species was prepared on the basis of published literature and personal interviews. These were screened in

accordance with botanical and economic characteristics, with emphasis on previously uncultivated species. Certain agricultural plants were also considered.

Factors such as yield potential, cultural requirements, tolerances to physiological stress, production costs, and land availability were considered in ranking the candidate species of each region (2). Plants with yields less than 2.2 tons/acre (5 metric tons/hectare) were eliminated. For the potential energy crop species comparisons were drawn with six categories of economic plants, including tall and short broadleaves, tall and short grasses, legumes, and tubers. Some 70 species were recommended for consideration in the program's second phase (field screening). Some of these plants (redroot pigweed, lambs-quarters, Colorado river hemp, ragweed) have no prior history as cultivated crops and their cultural needs remain obscure. Other species (Bermuda grass, Kenaf, reed canary grass, sudan grass) have been improved and cultivated for decades (2).

BOTANICAL AND AGRONOMIC CONSIDERATIONS

The initial steps taken by DOE to evaluate herbaceous land plants will help to clarify their value as a renewable energy source. However, an extensive research effort is needed to complete this task even as it applies to existing plant forms already managed as agricultural crops. A continuing effort will be needed over a period of several decades in the areas of new species evaluation, genetic improvement, herbaceous plant cropping on marginal lands, and crop tailoring to changing energy needs. The remainder of this paper offers some general guidelines and considerations for dealing with the vast pool of existing herbaceous land plants.

1. Botanical Considerations:

(a) Photosynthesis: Photosynthesis is the process by which the radiant energy of sunlight is converted to chemical energy by plants. Its summary reaction can be stated simply as:

$$CO_2 + H_2O \xrightarrow[\text{Green Plants}]{\text{Sunlight}} (CH_2O) + O_2$$
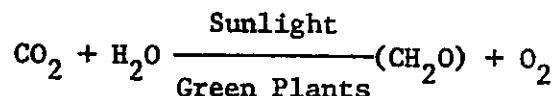
The amount of energy retained in the photosynthate (CH_2O) is about 468 kj/mole.

Although not an efficient process, it is the only system of solar energy conversion on earth that has operated at any appreciable magnitude and with any appreciable economy for any appreciable period of time. An estimated 1350 joules/m^2 arrives at the earth's upper atmosphere in the form of solar radiation but only about half penetrates to the earth's surface (28). A theoretical 8 percent of this radiation could be converted photosynthetically; however, a maximum conversion efficiency of only 4 percent has been attained and this under conditions of low light intensity (29). Agricultural plants average perhaps 0.5 to 1.0 percent efficiency. Land plants on a world-wide basis probably average less than 0.3 percent efficiency. Nonetheless, the earth's plants store annually about 10 times more energy than is utilized, and some 200 times more than is consumed annually as food (30).

Photosynthesis consists of two phases: (a) Energy capture, yielding chemical energy and reducing power; and (b), the reduction or "assimilation" of atmospheric CO_2. The carbon reduction phase is accomplished by three distinct pathways (C_3, C_4, and CAM). Each pathway is found among the world's herbaceous land plants, but the C_3 pathway is the most widely distributed. CAM plants, which assimilate carbon at night, are relatively less important eventhough their utilization of water is generally more efficient than for C_3 species. The C_4 pathway

was at first thought to reside only in sugarcane and related tropical grasses (31,32,33). It was soon found in temperate plants such as Zea, Sorghum, and Amaranthus (34-38). The C_4 species constitute a kind of apex in photosynthetic proficiency, aided to some extent by attributes such as a low CO_2 compensation point, a "lack" of photorespiration, and a capability to utilize both lower and higher light intensities than do C_3 and CAM species (5,9,39).

An important aspect of photosynthetic energy conversion often overlooked in higher plants is their "spectral proficiency", that is, their ability to convert different regions of the sun's spectral energy distribution. When photosynthesis by a given leaf is measured at different wavelengths of equal quantum flux, say from 400 nm in the blue-violet to 720 nm in the far-red, a photosynthetic action spectrum is attained which tells us much about the leaf's ability to "harvest" the entire package of visible light energy received from the sun. With sufficient replications an action spectrum characteristic of the species is derived, a kind of spectral finger print complete with peaks and depressions typifying that species. Ironically, more than 60 percent of incoming solar energy is received at wavelengths shorter than 550 nm, while (apparently) most plants are photosynthetically active at wavelengths longer than 600 nm. There is some evidence that Saccharum and a few other species have major photosynthesis activity in the blue-violet to blue-green region (40,41). Photosynthetic action spectra have been determined for approximately 30 agricultural plants (40-45). The vast majority of herbaceous land plants have not been examined in this context.

(b) <u>Photosynthesis</u> <u>in</u> <u>an</u> <u>Energy</u> <u>Crop</u> <u>Perspective</u>: A plant physiologist or biochemist measuring photosynthesis in the laboratory usually determines the quantity of CO_2 assimilated per unit of leaf area in an hour or some other convenient time interval ($mg\ CO_2/cm^2/hr^{-1}$). It does not necessarily follow that superior assimilation rates noted under these conditions will translate to high photosynthate yields in the field. A more convenient measure of photosynthetic potential in biomass-candidate species is the quantity of dry matter produced per square meter of leaf surface per day ($g/DM/m^2/day$). A majority of herbaceous land plants would produce in the order of 2-8 grams of oven-dry material per square meter per day, <u>during the peak of their growth or tissue-expansion phase</u>. A yield of 15 $g/m^2/day$ would be quite good and would typify some C_4 pathway species. Potential maximum yield estimates have been placed at 34 to 39 $g/m^2/day$ for C_3 plants and 50-54 $g/m^2/day$ for C_4 plants (46).

To an energy planter the most meaningful measure of solar energy conversion to biomass is the number of kilograms of dry matter produced per hectare per year (or tons per acre per year). While photosynthetic processes <u>per se</u> remain an important factor, equally important are all other processes and constraints of plant growth and development which come into play as photosynthate is elaborated to harvestable biomass. Each of these factors finds expression in the energy planter's gross yield of biomass. Annual dry matter yields in the order of 22,500 kg/ha (10 tons/acre) are common for a few species but the majority of herbaceous land plants probably yield less than 4500 kg/ha (2 tons/acre).

The reckoning of dry matter yields on an annual basis rather than an hourly or a daily basis might seem inappropriate to non-woody species whose growth period lasts only a few weeks or months. However, it is correct to do

so since many of the energy planter's expenses (including land rentals, taxes, equipment depreciation, and land maintenance) are incurred on an annual basis (9,47,48). Moreover, some herbaceous plant species do produce dry matter continually throughout the year and others could do so if managed as energy crops. A plant such as sugarcane propagated as a 12-month sugar crop can yield dry matter at the rate of 10-12 g/m^2/day, or about 10 tons/acre/year. The highest dry matter yields attained to date by the author were with first-ratoon sugar-cane managed for total biomass rather than sugar. These amounted to 36.6 tons/acre year, or 26.6 g/m^2/day over a time-course of 365 days (49).

It is safe to say that for most plants there is no direct relationship between photosynthetic potential, as determined in the laboratory, and the total dry biomass to be harvested in the field. The principal reasons for this are a series of botanical and agronomic factors which prevent the elaboration of photosynthate to biomass at rates commensurate with the plant's carbon reduction potential. Some of these factors are fundamental constraints against growth and development essentially beyond the control of the energy planter (though sometimes controllable by the plant breeder). Other constraints are a reflection of plant management and can be eliminated through research and development of the species as an energy crop.

It is also safe to say that some non-woody land plants will be found to have good biomass potentials but little prospect of ever being managed as agricultural energy commodities. For such plants a decisive attribute will be their ability to survive and produce some biomass with the barest minimum of production inputs (8 , 9). Yet even in these instances one must not over-emphasize photosynthesis rate as an energy yield indicator; there is simply too much variability in the measured rates of photosynthesis and too little

correlation with measured biomass yield (5,33,50). An example of this was found in a series of "wild" sugarcanes (Saccharum species) whose photosynthesis rates varied by a factor of 10 while their biomass yields varied by a factor less than 2 (40). Variation is similarly high among the hybrid sugarcanes of commerce (33,51). In a given field of sugarcane, completely uniform as to soil series, variety, planting date, and cultural management, one can expect to find photosynthesis and growth rates that vary by a factor of 3 to 5 among randomly-selected sampling sites (5).

(c) Reduction State of the Primary Photosynthate: To this point we have considered biomass as "elaborated photosynthate", consisting mainly of cellulose, and lignin derived from glucose or polyglucosides having the basic formula ($C_6H_{12}O_6$). This is quantitatively the most important form of biomass for both woody and herbaceous plant species. However, as a form of stored energy it has the limitation of being only partially reduced. The presence of oxygen in the structure of plant tissues, starch, and extractable sugars limits the energy content of such materials to approximately $14-16 \times 10^6$ BTUs per dry ton. Alternately, some plant species store energy in more highly reduced compounds having progressively less oxygen in their structure. Plant materials such as isoprene polymers, sterols, oils and waxes consist mainly of carbon and hydrogen and contain in the order of $40-50 \times 10^6$ BTUs per dry ton. Calvin and others have advocated the study of "hydrocarbon plants" as superior biomass energy sources (22,21,52). Many of these species have the added advantage of good adaptability to lands that are semi-arid, roughly-contoured, and otherwise marginal for the production of more conventional food and energy crops (8,53,54).

Hydrocarbon-bearing plants include both woody and herbaceous species. Some of the better-known examples, such as the rubber tree (Hevea brasiliensis)

and guayule (Parthenium argentatum), are woody perennials, while others, such as Euphorbia and Calotropis species, are borderline cases that could be managed either as forest or agronomic energy crops. Milkweed species (Asclepidacea) are predominantly herbaceous, but one member found in the tropics, Calotropis procera (the "giant milkweed"), is a woody perennial reaching heights of 9 to 12 feet over a period of several years. In Puerto Rico it is regarded as a forest specimen (55), but as an energy crop would most likely be managed as a frequently-recut forage (56). Hydrocarbon-bearing land plants as a group have been generally underexplored by the ERDA and DOE biomass energy programs.

(d) Water Utilization Efficiency: Water will quite definitely be a decisive limiting factor in the worldwide expansion of agriculture (54, 9, 57, 58). It is therefore important that water utilization efficiency be considered in the future screening and development of herbaceous land plants as energy resources. Three factors must be assessed from the onset: (a) Utilization efficiency in photosynthetic processes; (b) water extracting capability from the candidate species' natural terrain; and (c), the species capacity for water conservation by anatomical means.

Among candidate herbaceous species the efficiency of water utilization will be influenced markedly by the plant's pathway of carbon reduction. C_4 species should tend to reduce more carbon per unit of water transpired than C_3 species but less than plants using the CAM pathway. C_4 plants such as sugarcane (59,4) have a lower mesophyll resistance (r_m) than C_3 plants, favoring in turn a steeper CO_2 gradient between the atmosphere and photosynthetic reaction sites in the leaf. CAM plants have an r_m comparable to C_4 plants, but they assimilate carbon at night when transpirational water loss is at a minimum. The CAM pathway in effect is a plant water conserving mechanism.

Intensively-cultivated herbaceous plants, such as sugarcane, require about 150 mm of water per month (6 inches) to sustain maximum growth (60,61,54). Most herbaceous plants having some potential as biomass resources will not receive that quantity of water as rainfall nor are they likely to be given this quantity as irrigated crops. An important feature of any herbaceous plant screening program for arid or semi-arid regions would be the selection of deep-rooted (or tap-rooted) and thick-leafed candidates having the capability to draw upon subsoil water and to conserve water used in tissue expansion. Irrigation for such species would be confined to the planting period to aid germination or plant establishment. Considering that virtually all regions of the U.S. receive adequate rainfall on a seasonal basis, some effort should be made to identify herbaceous species that will survive arid conditions and produce a "flush" of biomass when rainfall is adequate to do so. Examples of herbaceous plants that do this include milkweed, tansy (Tanacetum), ragwort (Senecio), alfalfa, and most Euphorbia species.

2. Agronomic Considerations:

The production of biomass involves the collaboration of physiological, biochemical, botanical, and agronomic factors under any set of conditions. However, for the intensive management of biomass production, particular attention must be given to field-scale behavior of plant masses in which an individual plant or crown complex loses the importance we attach to it as a botanical or horticultural entity. Several agronomic considerations critical to successful biomass production are herein discussed.

(a) Growth Characteristics: To attain maximum biomass on a per annum basis one would ideally select a year-round growing season and plant species capable of growing on a year-round basis. Certain tropical grasses (sugarcane,

napier grass, Johnson grass, bamboo) do this very nicely if planted in the tropics. Some of their members produce well also in sub-tropical or even temperate regions, but given equal management they will realize only part of their full yield potential when growth is constrained for several months by cool temperatures.

It is important to recognize also that growth is a 24-hour process as well as a 12-month process. The photosynthetic and tissue-expansion systems that operate each day are fully dependent on the nocturnal transport and mobilization of growth-supporting compounds. For this reason the tropics are again favored by their warm nights for biomass production. In a similar vein the cool nights of the southwestern arid lands are probably as restrictive for biomass as are the limited moisture supplies.

Possibly the most desirable growth characteristic of all for herbaceous species is the ability to produce new shoots continually throughout the year, year after year, from an established crown. This is a predominant characteristic of sugarcane and certain other tropical grasses both related and unrelated to Saccharum species. Such plants do not require the periodic dormancy and rest intervals so important to most temperate species. Nor is this compensated by the intensive flush of May-June growth by temperate plants—over the course of a year the slower-growing tropical forms will out-produce them by a factor of three or four.

A less obvious but utterly critical feature of the perennial crown is its continual underground contribution of decaying organic matter to the soil. This process proceeds concurrently with the continuous renewal of underground crown and root tissues. For this reason the long-term harvest and removal of above-ground stems, together with the burning off of "trash", does not have an adverse effect on sugarcane lands. There are soils in Puerto Rico that have produced

sugarcane more or less continually for four centuries without destruction of their physical properties or nutrient-supplying capability. On the other hand, seasonal crops such as field corn and grain sorghum do not develop a perennial crown. For these plants a good case can be made against the removal of above-ground residues from the cropping site.

(b) Tissue Expansion vs Maturation: A common misconception holds that biomass growth involves mainly a visible increase of size, and that per acre tonnages of green matter are a reasonably accurate indicator of a plant's yield potential. It is also frequently assumed that the moisture content of plant tissues is essentially constant at around 75 percent, and that dry matter yields can be calculated rather closely from green weight data. These assumptions are not correct in any case but are particularly erroneous with respect to herbaceous species. In virtually all such plants "growth" consists of discrete, diphasic processes of tissue expansion followed by maturation. The tissue expansion phase produces visible but succulent growth consisting mainly of water (in the order of 88-92 percent moisture). The maturation phase corresponds to physiological aging and senescence, that is, to flowering and seed production, slackening of visible growth, yellowing and loss of foliage, and hardening of the formerly succulent tissues. During this period the dry matter content will increase by a factor of two to four in a time interval that may be shorter than that of the tissue-expansion phase. For example, the hybrid forage grass Sordan 70A more than doubles its dry matter yield in a time-span of only two weeks (23), ie, during weeks 8 to 10 in a 10-week growth and reproduction cycle. For this reason the optimal period of harvest must be determined with care for each candidate species. Again, as a rule of thumb, the allowing of additional time before harvest will work in favor of increased biomass yields from herbaceous plants.

For most herbaceous plants the production of dry matter can be plotted as
an S-shaped curve (Figure 1). Dry matter content will not ordinarily exceed
10 to 12 percent during the period of rapid tissue expansion but will begin to
rise dramatically at some point in time that is characteristic of the individual
species. Dry matter will rarely increase beyond 40 percent in herbaceous plants.
Attempts to hasten this rise (by withholding water) or to delay it (by use of
growth stimulants) have met with limited success in tropical grasses (63). Some
increase in the magnitude of dry matter accumulation has been attained over short
periods of time with the plant growth regulator Polaris (63).

(c) Harvest Frequency: Once the diphasic nature of biomass growth and
maturation is recognized the importance of harvest frequency is also underscored.
The optimal period for harvest in the maturation curve of one species will differ
enormously from the optimal harvest period of another—even among varieties with-
in the same genus and species. For this reason it is convenient to group
candidate species into distinct categories based on the time interval that must
elapse after planting to maximize dry matter yield (63). The management and
harvest requirements of each group will also vary. On this basis it has been
convenient to organize tropical grasses into "short,-intermediate-, and long-
rotation" categories (Table 1).

As illustrated in Figure 2, the tissue maturation curves for typical members
of each category vary greatly over a time-course of 12 months. Hence, to
harvest sugarcane at the 10-week intervals favorable to Sordan 70A would yield
little dry matter. Similarly, any delay of the Sordan harvest beyond 12 weeks
is a waste of time and production resources. Napier grass, an "intermediate
rotation" species, is more than a match for sugarcane at two-and four-months of
age, and will nearly equal sugarcane yields at six months, but thereafter sugar-
cane will easily out-produce napier grass. In this context a short-rotation

species should be harvested four or five times per year, an intermediate-rotation species two or three times per year, and a long-rotation species no more than once per year. This need for careful attention to the maturation profiles of candidate species is underscored by yield data for sugarcane and napier grass harvested at variable intervals over a time-course of 12 months (Table 2).

It is also evident that, while Sordan and napier grass attain rather level plateaus for dry matter, sugarcane continues to increase dry matter beyond 12 months (Figure 2). Sucrose accumulation profiles are very similar for sugarcane. For many years sugar planters have taken advantage of this feature by extending the cane harvest interval beyond 12 months. Hence, the Puerto Rico sugar industry harvests two crops—the "gran cultura" (14 to 16 months between harvests) as opposed to the primavera crop (10 to 12 months between harvests). In Hawaii sugarcane is commonly harvested at two-year intervals.

(d) <u>Energy Crop Rotations</u>: From Figure 2 one would surmise that the energy plantation manager should plant a herbaceous species such as sugarcane and leave it there—up to 18 months if possible—before harvest. In addition to maximum fiber he would also harvest fermentable solids as a salable by-product. This reasoning would probably be correct in a tropical ecosystem suited to <u>Saccharum</u> species and where a regional tradition exists for sugar planting. However, these circumstances do not exist in many countries having an otherwise good potential for growing biomass. For example, there is no region of the U.S. mainland suited for 12-to 18-month cropping of sugarcane, although there are vast regions there suited to some form of tropical grasses. Hence, a future energy planter in Florida, Louisiana, southern California, or southern Texas might seriously consider whether he should harvest a 6 to 8 month crop of sugarcane per annum or two crops of napier grass in the same time-frame.

Equally important is the fact that some countries will not be able to afford a land occupation of 18 months by a single energy crop. This is especially true of densely populated, developing tropical nations having an urgent need for domestic food production (64). In such cases a short-rotation species such as Sordan may be the popular choice for energy planting since it can be sown as a stop-gap between the harvest of one food crop and the planting of another. In this capacity it would also prevent soil erosion and weed growth while acting as a scavenger for residual nutrients left over from the prior food crop.

Seasonal climate changes will also be a factor in the rotation of biomass energy species with conventional food and fiber crops. Short-rotation tropical grasses such as Sordan are ideally suited to the tropics—but they can be grown on a seasonal basis during the heat of summer in most temperate regions. Such plants could be propagated to maturity in a mid-June to mid-August time frame. In a given year the same site could produce a cool season food crop (a _Brassica_ species, spinach) or a cool season forage (ryegrass, fall barley) both preceding and following the biomass energy crop.

HARVEST AND TRANSPORTATION

Perhaps the weakest point in current production research for biomass is the lack of proven harvest equipment and methodologies for the maximized stands of biomass that each contractor strives to attain. This is most evident in woody biomass scenarios where conventional forest harvesting technology is either not applicable or simply doesn't exist in the context of silviculture energy plantations. The outlook for harvesting herbaceous land plants is considerably better but a good deal of research remains on harvest and post-harvest technology, together with equipment redesign and modification.

1. <u>Mowing</u> <u>vs</u> <u>Conditioning</u> <u>As</u> <u>Harvest</u> <u>Options</u>:

The vast majority of herbaceous land plants can be harvested nicely with the sickle-bar mower (assuming that land slopes and contours are otherwise suited for mechanized operations). This implement was designed more than a century ago as a replacement for the hand sickle and manual grass scythe. As a horse-drawn implement it revolutionized the harvest of grain and forage crops. Today it is usually operated from the power take-off of Class I and II tractors. The original wooden parts have been replaced, bearings and lubrication systems have been improved, and it is no longer geared to the slow forward pace of draft animals. But it operates on basically the same principle as its horse-drawn predecessors.

There are two principal limitations of the sickle-bar mower as a harvest implement for herbaceous biomass crops: (a) It is designed to operate in relatively low-density stands of plants, and (b), its cutting process is confined to a single slice near the base of upright stems. In other words it is a mechanized sickle for severing stems rather than a stem conditioner. This mower has a preference for dry and upright stems whose total mass does not exceed about 12 green tons per acre. It experiences real difficulty with wet and lodged materials and with plant stands in any condition whose mass exceeds 15 green tons per acre. Since its operation is based on a cutting principle the sickle must be kept continually sharp for effective performance. Its efficiency is immediately lowered by contact with mole hills, rocks, wires, scrap metal, and durable objects of any kind encountered in the field.

In the author's experience the modern sickle-bar mower operating in a typically dense tropical grass, such as Sordan 70A (about 20-25 green tons/ acre), will experience a frequent tripping of its "fail-safe" mechanism. This is a built-in feature of the implement designed to prevent its destruction when

striking unseen stumps or other fixed objects at operational speed. Nonetheless, the sickle-bar mower is probably very adequate for harvesting most herbaceous land plants, that is, those plants whose standing green mass will not exceed about 12 tons per acre at any given harvest interval.

For harvesting somewhat higher densities of herbaceous material a series of "flail" and "conditioner" designs have proven to be superior to the sickle-bar mower. Such implements do not perform on a cutting principle but rather break off the plant stem by striking it with extreme force. Sharpness of the contact blades is not a decisive feature, in fact they will perform fairly adequately even when dull from long use. These machines do require high horsepower (90 to 120 hp) and high PTO speed (1000 rpm).

The most effective implement of this type tested to date in Puerto Rico is the M-C "rotary scythe-conditioner". The plant stems are broken off by four lines of whirling blades and are repeatedly shattered as the blades restrike the stems at 3-to 5-inch intervals. The resulting "conditioned" biomass is evenly distributed in a broad swath behind the rotary scythe. In this state the subsequent drying and baling operations are more easily performed than with conventionally-mowed biomass, that is, with plant materials received in clumps and matts and with only one cut surface to facilitate water removal. An additional advantage of the rotary scythe-conditioner is its capacity to harvest plant densities roughly double those handled by the sickle-bar mower. A second added advantage is its ability to harvest lodged and wet materials. Such plants are harvested about as readily as those in a dry and upright condition. A third advantage is its relatively trouble-free operation. The number of parts subject to malfunction are purposely reduced to a minimum.

At this writing the rotary scythe-conditioner has given excellent performance in plant densities amounting to about 22 green tons per acre (62). It is believed that its upper density limit will be in the order of 40 green tons per acre (65).

Plant yields considerably higher than 40 green tons per acre are anti-cipated for a few herbaceous species. Sugarcane yields in excess of 90 green tons per acre year were recently demonstrated in Puerto Rico (49). Most sugar-cane harvesters marketed today begin to have difficulty with cane densities in the range of 50 to 60 standing green tons per acre (65). The most effective sugarcane harvester in Puerto Rico at present is the Class Model 1400. Orig-inally developed in East Germany, the Class is a single-row, whole cane harvester which employs a powerful air blast to remove organic trash and soil from the cane at the point of harvest in the field. It has accommodated over 60 tons of green cane per acre. With modifications it might possibly harvest 80 to 90 tons per acre (65).

2. Solar Drying:

A characteristic difficulty with biomass is its low density relative to fossil energy and its high water content which is costly to transport to processing centers. Wherever possible it is desirable to remove most of this water at the harvest site by solar drying. One exception to this is the use of "green" biomass for anaerobic digestion. Another exception is found in sugarcane. In this case the whole green stalk is transported to a centralized mill for dewatering. The plant's soluble fermentable solids are recovered there from the expressed juice and sold as refined sugar or molasses.

Very adequate equipment for the solar drying of non-woody land plants can be found in the cattle forage industry. The rotary scythe-conditioner described above does much to prepare herbaceous plants for rapid drying in the sun (66,67). Ordinarily these materials would be turned over once or twice in bringing the moisture content down to about 15 percent. Three windrows would then be combined into one shortly before baling. Each of these operations can be performed with

standard side-delivery forage rakes operating from the power take-off of a Class I or II tractor. When higher density biomass is to be raked (Sordan or napier grass) a heavy-duty "wheel" rake may be more suitable. These implements are also becoming standard equipment for forage-making operations.

3. Compaction And Baling:

Solar-dried biomass is rarely transported to its processing site today in a loose state, although once this was standard practice. For economy of space in transport and storage, as well as ease of handling, such materials are first compacted and then bound with a suitable twine or wire. The standard hay "baler" today is actually a compactor. It produces conveniently-sized cubes having a controlled density range of roughly 8 to 20 pounds per cubic foot. A typical hay "bale" would weigh 60 or 70 pounds and is easily handled by one man in transport and storage procedures or in cattle-feeding operations.

A different concept in biomass baling has appeared in recent years. This is the "bulk" or "round" baler which operates as a windrow wrapper rather than a compactor. This implement produces large cylindrical bales weighing up to 1500 pounds each (68,69). Since no appreciable compaction is involved the bale density is relatively low—in the order of 10 to 12 pounds per cubic foot. More recent modifications enable this machine to produce cube-shaped bales which are more economical of space during transport and storage. Both front-and rear-end loaders suitable for handling these bales are marketed as conventional tractor attachments (65).

There are two types of balers for sugarcane bagasse: The baling press and the briquetting press (70). The first type is a hydraulic press employing the same compaction principle used for hay. The bagasse is baled in a semi-green state and the formed cubes are tied with twine or wires to prevent them

from reexpanding. Their density will range from 25 to 40 pounds per cubic foot. Bales of this type must be stacked carefully to prevent <u>spontaneous</u> combustion, that is, with sufficient space between them to allow air circulation. The briquetting press operates with dry bagasse having a moisture content of 8 to 15 percent. This press provides high pressures in the order of 5,000 to 15,000 psi. Under these conditions extremely compact cubes are produced which retain their form without the use of twine or wires.

4. <u>Transport And Storage</u>:

Herbaceous biomass that has been solar-dried and baled can be transported to processing or storage sites without appreciable difficulty with existing equipment. However, this can entail a significant cost. Ordinarily such materials would be loaded directly in the field on a low-bed truck. Standard bales (60-80 pounds) can be loaded manually or with mechanical loaders requiring only one laborer on the truck for final positioning of the bales. Bulk bales would be stacked two layers deep on the truck bed with tractor-mounted loaders. The same truck would transport the biomass to a final processing or storage facility without intermediate transshipment operations. In the case of sugar-cane, the harvested whole stalks, or stem billets, whatever the case may be, are hauled in carts to the adjacent mill. The same materials could be carted to an intermediate reloading point for truck delivery to more distant sugar mills.

Delivery costs will vary considerably with the individual biomass production operation. As a general feature a 40-ton low-bed truck with driver can be hired for about $180 per 24-hour day. Loading equipment with operators must be stationed at each end of the delivery run. In an ideal biomass production operation, ie, one managed by a private farmer for profit, the land owner would

probably own and help operate the truck and accessory equipment. An estimated delivery cost for solar-dried biomass on a 20-mile run would be $6.00 to 8.00 per ton.

PRODUCTION COSTS

Published production costs for both herbaceous and woody biomass show broad variations that are both understandable and inevitable (48,58,6,7,3). A given contractor will want to present his speciality crop in the best possible light relative to the dollar inputs needed to obtain a million BTUs in biomass form. This topic was reviewed in detail recently in a USDA report by Kathryn A. Zeimetz (48). The author concluded that most biomass researchers greatly underestimate the cost of biomass production, excluding from their calculations significant indirect costs, long-term repercussions on ecosystem resources, future competition for land and water, and both the cost and efficiency of biomass conversion systems.

1. Obtaining Correct Cost Data:

A seriously misleading trend is to base the production costs of a biomass candidate on its published yield performance as a conventional food or fiber crop. Sugarcane is an appropriate example. In Puerto Rico, sugarcane managed for sucrose yields 25 to 30 green tons per acre year; as an energy crop it can yield 80 to 90 tons per acre year with only moderate increases in production costs (49). Napier grass data are similarly misleading. There is a wealth of printed matter on the yields of napier grass managed as a tropical forage crop, that is, when harvested repeatedly at five-or six-week intervals at moisture contents approaching 90 percent. As an energy crop napier grass produces roughly two to three times more dry matter per annum at less cost than the cattle forage (49).

2. Production Costs For Tropical Grasses:

Since June of 1977 considerable information has been gathered on production costs for sugarcane and other tropical grasses whose agriculture has been managed for maximum dry matter yield in a tropical ecosystem (62,63). A breakdown of production input charges for "energy cane" is presented in Table 3. These data pertain to a privately-owned, 200-acre operation yielding 33 oven-dry tons of biomass per acre year. Total cost, including delivery to the milling site, amount to $25.46 per ton or 1.70 per million BTUs. Under Puerto Rico conditions about 70 percent of this dry matter would be burned as a boiler fuel. The remainder would be extracted as fermentable solids during the cane dewatering process and later sold as constituents of high-test molasses. This is a solid credit to the insular energy cane planter owing to Puerto Rico's precarious reliance on foreign molasses as feedstock for her rum industry (71). Assuming a market price of $0.75 per gallon for high-test molasses the fermentable solids from one such ton of energy cane would be valued at more than $45.00, or about $1500.00 per acre. Cane milling costs today in Puerto Rico are about $4.50 per ton (72).

Production costs for Sordan 70A are presented in Table 4. Although Sordan's biomass yield is lower than that of energy cane, production input costs are also lower. The final cost of an oven-dry ton of Sordan 70A is about $24.00, or $1.50 less than a ton of energy cane. In this instance there is no sale of fermentable solids. Production costs for napier grass would be modarately lower than Sordan 70A owing to a much higher yield per acre year for napier grass (49,62). This crop similarly has no sales of fermentable solids.

3. Management As A Production Cost Factor:

Production costs for energy cane listed in Table 3 include "management" as 10 percent of the cost subtotal. This is an indefinite term covering the

administrative skills expended by way of good agricultural technique to maximize biomass yield. It also reflects the morale (or profit incentive level) of the individual grower or institution in charge of production.

The management factor contribution to future biomass production scenarios can range from very good to very bad, but it will have the potential to be decisive in all production operations. Again, using sugarcane as a convenient example, it is common knowledge that litte profit is to be made anywhere in the world today by planting sugar, but it is the well-managed operations that will minimize losses and offer the best prospect of survival until sugar values are again equitable. At one extreme superior management will be found in privately-owned plantations which in some countries are still basically family operations. Here the land owner has an inherent interest in his property and capital invest-ments and possesses the skills and incentive to make a good living from agriculture. Such individuals can still be found today, for example, in the Queensland sugar industry. At the other extreme is the government-owned production operation. Historically, governments have not made good farmers. A farm manager who has little incentive to make a profit and who cannot be held accountable when making a loss will ultimately have the inferior production record.

Government take-over of an agricultural commodity is sometimes viewed as a necessary intervention in a free market where important social or political considerations could not otherwise be served (73). This was the case with sugar-cane in Puerto Rico where a large and otherwise unemployable labor force could no longer be sustained by private interprise (64,79). As a consequence it now costs about 28 cents to produce a pound of sucrose in Puerto Rico, at a time when its value on the world sugar market is only about 14 cents per pound. It is fair to say that management is not the only factor contributing to high production costs—environmental quality standards have also had a negative impact on the PR sugar industry (29)—but poor management is clearly the main contributing factor.

In a well-managed production scenario for herbaceous terrestrial biomass some straight-forward steps will need to be taken to assure maximum returns from production input expenditures. These will include the following: (a) Correct land preparation, including land leveling and planning where needed; (b) correct design and installation of the irrigation system; (c) correct seedbed preparation; (d) careful selection and treatment of seed; (e) correct seeding (relative to depth, density or row spacing, and season); (f) reseeding of vacant space when necessary; (g) correct pest control programs (including administration of control on weekends and holidays when required); (h) maintenance of correct irrigation, fertilization, and cultivation programs; (i) correct timing and synchronization of harvest operations; (j) correct selection and use of harvest equipment; (h) post-harvest maintenance of land and machinery.

For most biomass crops the costs of these measures will accrue whether they are performed correctly or not. The decisive factor will be the skill and motivation of the operation's field managers. Good management can best be assurred when production is retained in the context of privately owned plantations that are operated for personal profit.

SUMMARY

The nature of herbaceous land plants and their potential usefulness as a future energy resource is presented in broad outline. The large number of herbaceous species found in both cool and warm climates and in both the wild and cultivated state suggests that at least a small percentage of these could become valuable sources of fuel. Extensive screening will be needed in a range of ecosystems to bring the number of candidate species to a manageable level. Both botanical and agronomic features to be evaluated during the screening process are briefly discussed. Some of the production and harvest operations required of

herbaceous plants as agricultural commodities are also reviewed, together with partial cost analyses for the production operations. Management of the energy crop is seen to be the decisive cost input. This factor will be optimized in privately-owned operations motivated by a strong profit incentive.

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TABLE 1. Categories of Tropical Grasses and Leading Candidate Clones Under Investigation as Renewable Energy Sources in Puerto Rico 1/

Category	Harvest Interval (Months)	Candidate clones
I. Short Rotation	2-4	Sordan 70A 2/ Sordan 77 2/ Trudan 5 Millex 23 Bermuda Grass NK Hybrids Roma (Sorghum)
II. Intermediate Rotation	4-6	Common Napier Grass (Var. Merker) Napier Hybrid PI 30086 2/ Napier Hybrid PI 7350 NK Hybrids Saccharum spontaneum: US 67-22-2 US 77-70 SES 231 S. spont. Hybrid (Wild) Intergeneric Hybrids
III. Long Rotation	12-18	Saccharum Hybrids NCo 310 PR 980 2/ PR 64-1791 B 70-701 US 67-22-2 2/ USDA Imports

1/ DOE Contract No. DE-AS05-78ET20071.

2/ Underlined clones are leading candidates for their category.

TABLE 2. Dry Matter Yields of Sugarcane and Napier Grass Harvested at Variable Frequencies Over a Time-Course of One Year 1/.

Interval (Months)	No. Of Harvests	Species	Tons DM/Acre/Year For —	
			Plant Crop	1st Ratoon Crop
2	6	Cane 2/	6.5	3.3
		Napier 3/	12.7	11.9
4	3	Cane	11.1	11.9
		Napier	22.6	25.1
6	2	Cane	16.6	20.6
		Napier	25.6	33.0
12	1	Cane	25.5	33.6
		Napier	19.3	25.8

1/ DOE Contract No. DE-AS05-78ET20071.

2/ Computed mean of three varieties and two row spacings.

3/ Computed mean of one variety and two row spacings.

TABLE 3. Dry Matter Production Costs for First-Ratoon Sugarcane Managed
as an Energy Crop 1/

Land Area: 200 Acres
Production Interval: 12 Months
DM Yield: 33 (Oven-Dry) Short Tons/Acre; Total 6600 Tons

Preliminary Cost Analysis

Item	Cost ($/Year)
1. Land Rental, at 50.00/Acre	10,000
2. Seedbed Preparation, at 15.00/Acre	3,000
3. Water (800 Acre Feet at 15.00/ft)	12,000
4. Water Application, at 48.00/Acre Year	9,600
5. Seed (For Plant Crop Plus Two Ratoon Crops), 1 Ton/Acre Year at 15.00/Ton	3,000
6. Fertilizer, at 180.00/Acre	36,000
7. Pesticides, at 26.50/Acre	5,300
8. Harvest, Including Equipment Charges, Equipment Depreciation, And Labor	20,000
9. Day Labor, 1 Man Year (2016 hrs at 3.00/hr) 2/	6,048
10. Cultivation, at 5.00/Acre	1,000
11. Land Preparation & Maintenance (Pre-& Post-Harvest)	600
12. Delivery, at 7.00/Ton/20 miles of Haul	46,200
13. Subtotal:	152,748
14. Management: 10% of Subtotal	15,275
15. Total Cost:	168,023

1/ DOE contract no. DE-AS05-78ET20071.

2/ Labor which is not included in other costs

Total Cost/Ton: (168,023 ÷ 6600): 25.46
Total Cost/Million BTUs: (25.46 ÷ 15): 1.70

TABLE 4. Dry Matter Production Costs for Sordan 70A [1]

Land Area: 200 Acres
Production Interval: 6 Months
Sordan 70A Yield: 15 (Oven Dry) Short Tons/Acre, Total 3,000 Tons

Preliminary Cost Analysis

Item	Cost ($)
1. Land Rental, at $50/Acre Year	5,000
2. Water (Overhead Irrigation), 360 Acre ft	2,160
3. Seed, at 60 Lbs/Acre	4,800
4. Fertilizer	10,000
5. Pesticides	4,000
6. Equipment Depreciation (6 mo.)	2,650
7. Equipment Maintenance (75% of Depreciation)	1,988
8. Equipment Operation (75% of Depreciation)	1,988
9. Diesel Fuel	2,200
10. Day Labor (90.00/Day for 140 Days)	12,600
11. Delivery, at 6.00/Ton	18,000
12. Subtotal:	65,386
13. Management (10% of Subtotal)	6,538
14. Total Cost:	71,924

[1] DOE contract no. DE-AS05-78ET20071.

Total Cost/Ton: (71,924 ÷ 3,000): 23.97
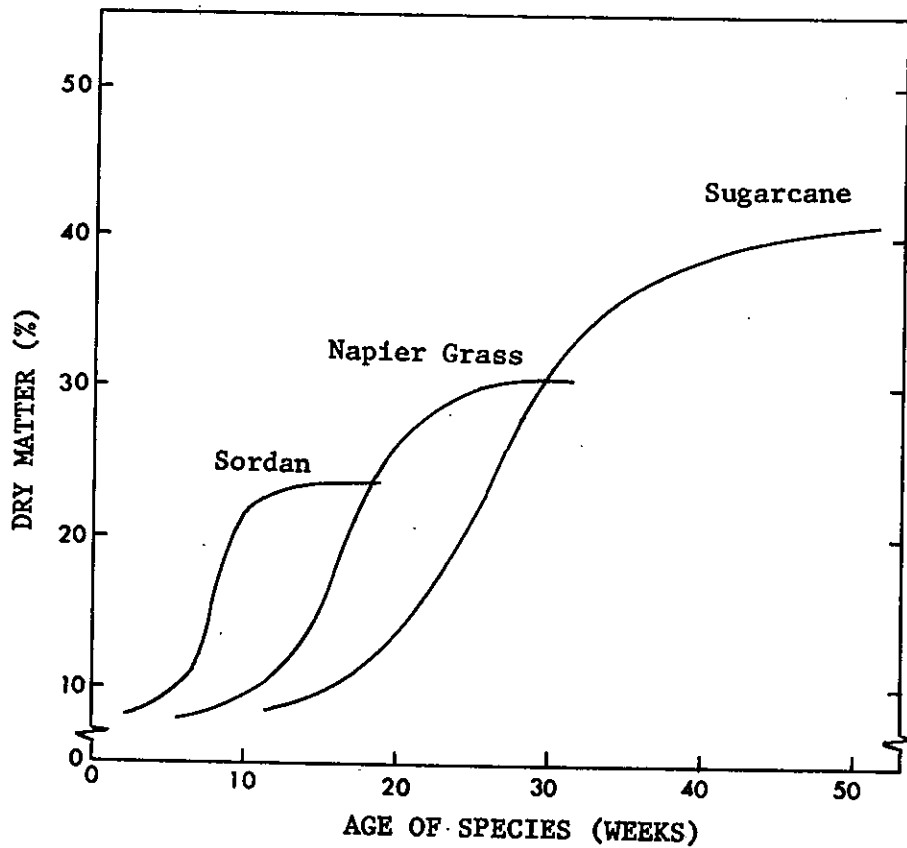Total Cost/Million BTUs (23.97 ÷ 15): 1.59

Figure 2. Relative maturation profiles for Sordan 70A, napier grass, and sugarcane over a time-course of one year. These plants are representative of the short-, intermediate-, and long-rotation cropping categories, respectively.
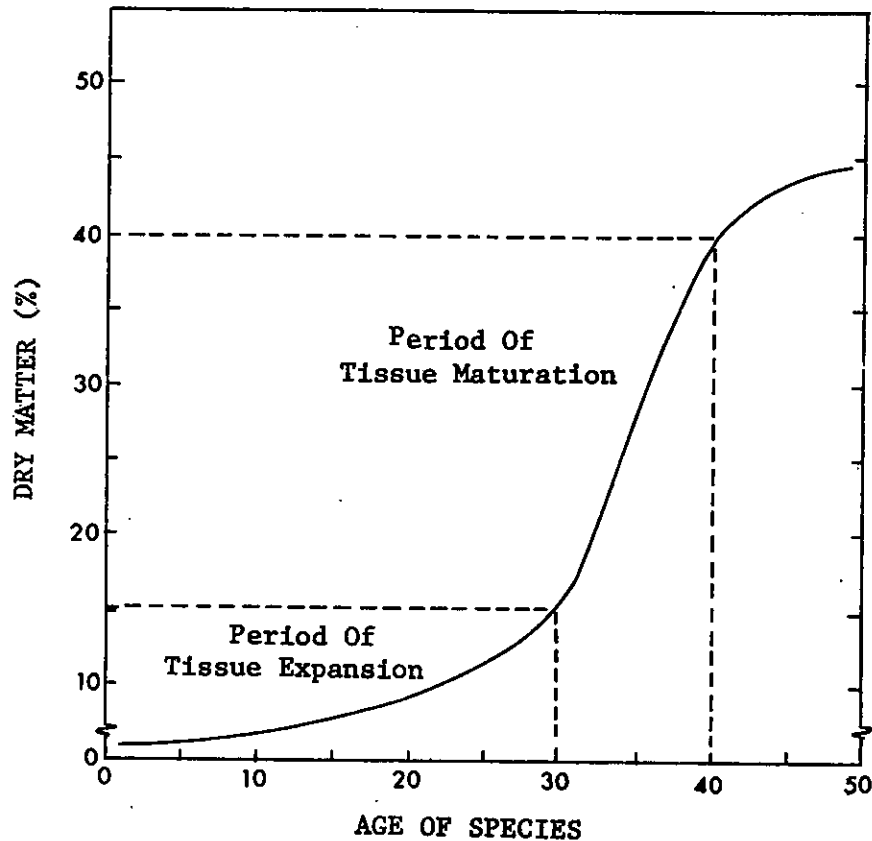
Figure 1. A generalized representation of the maturation profile of herbaceous land plants. While no specific time-frame or plant form is depicted, the diphasic process of tissue expansion followed by maturation is typical of non-woody plant species. With the visible growth phase essentially completed, the energy planter will gain much additional dry matter by allowing a brief additional time interval to elapse before harvest.