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A New Class of Plants for a Biofuel Feedstock Energy Crop

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Abstract

Directly burnable biomass to be used primarily in steam boilers for power production has been researched and demonstrated in a variety of projects in the United states. The biomass typically comes from wood wastes, such as tree trimmings or the byproducts of lumber production, or from a cash crop, grown by farmers. Of this latter group, the main emphasis has been utilizing corn stover, or a prairie grass called switchgrass, or using tree seedlings such as willow. In this article, I propose an alternative to these energy crops that consists of several different herbaceous plants with the one consistent property that they annually generate an appreciable bulk of dried-down burnable mass. The fact that they are a set of plants (nine are offered as candidates) gives this energy crop a great deal of flexibility as far as growing conditions and annual harvest time line. Their predicted yield is impressive and leads to speculation that they can be economically feasible.

Index Entries: Biomass; biofuel; energy crop; sclerified stalked plants; stiff stalked plants.

Introduction

The prospect of biomass as a fuel source is an alluring one. In the first place, it is geopolitically simple; most countries desiring to utilize it can provide their own biomass. In addition, many forms of biomass-to-energy conversions are CO_2 friendly, adding no net CO_2 to the atmosphere or at least no additional CO_2 other than would have naturally taken place. Probably the most exciting aspect of biomass fuels is that they are replaceable; there is no doomsday worry about using up all of Earthís resources. Indeed, some types of biomass are not only replaceable but also renewable; they are or can be created at the same rate that they are used.

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For all of the advantages of biomass fuel sources, there are two distinct drawbacks. First, biofuels do not economically compete with conventional (oil, gas, coal) fuels. It costs more to generate electricity from biomass compared to coal, and it costs more to power automobiles using biomass fuels compared to gasoline. Second, and probably more important, the sources of biomass are quite diffuse and may not be available in sufficient quantities to make a national impact as an energy use. Biomass is defined as organic material from animals, such as manure, or plants such as trees, grasses, and agricultural crops. Common examples are sawdust as a byproduct of milling wood, rice husks as a byproduct of food production, and pallet and wood crate discards. Ohio claims to produce <1% of its electricity with biomass, and it does it with "forest wastes, such as tops and limbs, and wood wastes, such as sawdust, chips, barks, and edgings" *(1)*. Most of this electrical generation is done within the wood-manufacturing industry *(2)* and is primarily used internally by the company that generates it.

Plant biomass can also come from "energy crops." Energy crops are "crops developed and grown specifically for fuel. These crops are selected to be fast growing, drought and pest resistant and readily harvested to allow competitive prices when used as fuel" *(3)*. The prospect that farmers will use portions of their vast acreage to produce a material that can be used for fuel seems to have a ring of creditability to it. Whether the power industry can pay the farmers enough to turn their heads away from the familiar markets of soybean, wheat, and corn is another issue. Farmers can provide the *quantity* of material to make biofuel a significant factor in the energy source equation.

Energy crops, or biofuel feedstocks, "under development in the US include hybrid poplar, willow, switchgrass, and eucalyptus" *(3)*. Indeed, prospective energy crops appear to come from both ends of the spectrum of the plant kingdom—monocot herbaceous plants, on the one hand, to more sophisticated hardwood trees, on the other. Switchgrass is a prairie grass (monocot) that grows favorably in the plains states and southwestern states. It dries down to give a burnable product, and the crop has benefited from significant amounts of research performed in states such as Iowa *(4)*, Wisconsin, and Texas and from the Department of Energy through Oak Ridge National Laboratory. On the other hand, willow is a tree, a woody plant whose trunk has annular rings such that it adds woody matter annually to its stem. It appears to be the favored energy crop under investigation in East Coast states, particularly New York where coburning with coal has produced some electricity *(5)*. Both of these energy crops have their proponents, both have been the subject of a considerable amount of research and demonstration over the past 10–15 yr, and both are looking more and more promising.

The intent of this article is to introduce another type of plant into the energy crop mix. Of this new type, I suggest nine specific species. These species come from the center of the plant kingdom, *between* monocots (grasses) and woody plants. All are herbaceous, either annual or perennial. The one common characteristic to all is that their stems die off annually and dry down to give a brittle stiff and relatively hard skeleton. These "remains" of the plant consist primarily of organic carbon-rich compounds and become a source of energy (fuel). Herein, they are referred to as stiff stalked plants (SSPs).

Before introducing and discussing these plants on an individual basis, and in order to understand the significance of the measurements made on and the comments made about each, some consideration should be given to plant botany as it relates to the characteristics of a good energy crop. Plant botany or physiology takes on a completely different thrust when viewed from the perspective of using the dead and dried stem for the ultimate purpose. A plant skeleton is really much different, and much simpler, than its living counterpart.

Plant Skeletal Physiology

The skeletal remains of a plant may look quite different than it did as a living entity. For trees, the skeletal remains look, for many years, almost exactly like the living plant. Truly the only telltale sign that the plant is dead is the lack of leaves. Conversely, the skeletal remains of a succulent herbaceous plant are almost nonexistent. It "melts away," leaving virtually no trace of its previous existence.

The difference between these two examples is the tissue construction of the living plant. Although there are a variety of tissue structures in each plant, the basic cells in succulents are thin walled and filled with a dilute solution of carbohydrates and other organic molecules. The cellulose present in the cell walls outside those cells is bathed in aqueous solution. At the first frost, the water freezes and enlarges the cell past its burst point, which then thaws to allow the water to drain out and leave no remaining structure. The plant "melts" to the ground and disappears rapidly.

The cells of woody plants have thick walls and encase a stronger, thicker solution of carbohydrate and cellulose. The freezing point of this solution is much lower than that of water, and if the cells do freeze, the cell walls are able to withstand the hydrostatic force, and therefore remain intact *(6)*.

To be more specific, the wall of a plant cell consists of three layers: primary wall, middle lamella, and secondary wall. The primary wall is thin and the middle lamella is more an adhesive gel than an actual structure. It is the secondary wall that is thick and gives the rigid structure to the cell. In a succulent, the secondary cell wall does not develop and the cell wall has little mass or strength. In cells of a woody plant, not only is the secondary wall thick but often it contains the organic compound lignin. Lignin is a material that is high in carbon, very hard, and very strong. Succulent plants contain virtually no lignin and therefore have a fragile structure and leave almost no skeletal remains. Nut shells are high in lignin and take on an almost rocklike hardness, and their skeletal remains look identical to those of their live counterpart. Lignin is the second most abundant organic compound on earth, second only to cellulose. Woody plant species typically contain 15–25% lignin. Lignin has a higher carbon concentration than cellulose and therefore has a high heating value.

In herbaceous plants that have persistent lignified stalks ("sclerified stalks") (stems), the variety of tissues in the stem may have characteristics of succulents and some may have characteristics of wood. The result is that the skeletal remains may have some components that remain intact after death and others that essentially disappear.

To describe what the stem of a skeletal herbaceous stalked plant looks like, we begin with the stem parts of a living plant. The parts of a vascular plant stem, be it herbaceous or woody, are basically the same. The stem consists of epidermis (for outer protection), phloem (for transport of food to the plant), xylem (for transport of water to the upper reaches of the plant), and pith (a center core for the incubation of new cells). Of these four parts, the bulk of the mass of the stem cross section consists of xylem and pith. The pith is usually a very light, spongy, almost styrofoam-like material. In wood, pith is almost nonexistent except in new bud stems. In stalked herbaceous plants, the pith is a significant part of the stem.

It is in the xylem that the mass of the stem resides. Both in woods and in stalked herbaceous plants, the burnable portion of the stem is primarily xylem. If the overall purpose of an energy crop is to fix carbon from the CO_2 of the air into a solid form that can be burned for the release of heat, then an energy crop must be one that accomplishes this fixation the best. The fixing of carbon is done through the photosynthesis process while the storing of that carbon is accomplished by the creation of cells and cell walls, which comprise tissue. The photosynthesis process is powered by sunlight; therefore, biofuel energy sources are really one type of solar energy. A good energy crop must not just "fix" carbon but store it as burnable mass. Considering the other demands for the energy the plant may have, such as making leaves, and making fruit or seeds, an energy crop is a plant that efficiently makes harvestable biomass.

To best describe the ability of a plant to create xylem, there are some technical indicators that can be used. Figure 1 illustrates that an SSP skeletal stem is basically tubular. The "tube" itself is primarily xylem because the epidermal phloem and pith cell walls are usually very thin. For energy crops, it is best to have this tube as large and substantial as possible. In monocot plants and some dicots, the xylem and phloem are not created in tubes but are "bundled" together as highly efficient string elements that are located in the pith. There is not much mass to these bundles and, therefore, not much mass to their skeletal remains. SSPs typically are the dicots that do not form xylem bundles but, rather, xylem rings.

Critical parameters concerning the skeletal stem include the stem diameter (D); the ratio of the stem diameter to the pith core diameter (D/P); the xylem thickness/pith diameter ratio (X/P); and the xylem-to-pith ratio, defined as XPR. The reason for both X/P and XPR is that X/P

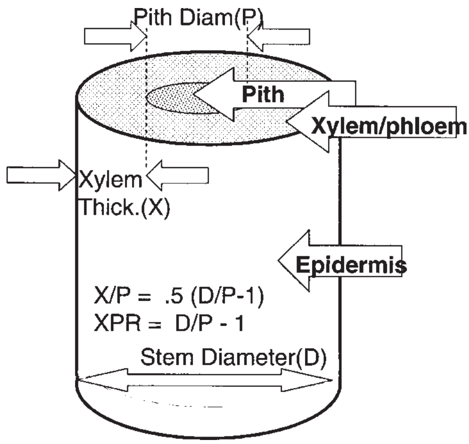

Fig. 1. Geometry of sclerified stalked plants.

ratios the single wall thickness against the total pith diameter, while *XPR* ratios twice the xylem wall thickness against the pith diameter (or the wall thickness against the pith radius). Another important physical property of the stem is the density of the dried xylem tissue (kg/m^3).

Description of Nine Candidate SSPs

The search for a crop that can be grown as an energy fuel begins by finding fast-growing plants that develop a significant xylem ring in their stem. Growth capacity can be estimated from several measurable factors. First is the size or weight of the individual dried-down stalk. Second is the field density at which it can be planted (stalks/ft^2. Third is the density of the material itself (kg/m^3). As each plant species is introduced in the following sections, the physical characteristics of the plant are given to make the growth capacity estimation.

Although one important criterion for an energy crop will be the bulk of burnable mass that can be harvested, per acre, there will be other factors as well. For instance, it may be important for a plant to "dry down" quickly, so it can be taken immediately from field to burner. It may be important that the burnable portion of the plant be easily cut and handled with conventional harvest equipment. It may be important that the plant cause no ill effects to the local population where it is grown and to the workers who harvest it. The type of seed and their dormancy period may be an important consideration. Does it keep for periods of time without rotting? There are some political implications for some of the candidate plants, for they may have been categorized as "invasive plants" or more seriously placed on a list of "noxious plants." Their introduction into certain geographic regions may be forbidden. Therefore as each plant species is introduced next, general information is provided that may be significant in evaluating its potential *(7)*.

Fig. 2. New England Aster blooms.

New England Aster (Asteraceae novae-angliae) *(Fig. 2)*

New England Aster is a wildflower that has such a beautiful and hardy purple-violet flower that it has been domesticated and offered to gardeners as an autumn flower. Although it is a perennial, a multitude of seeds are dried from the flower and scattered each year. The stem has extended branches primary at its top and grows to a height of 2 m. Mostly it grows in a single stalk, but certain types grow as bushes and others grow in several stalk clusters.

Seeds are available commercially and there is sufficient experience with the cultivation of New England Aster to suggest the best planting time, germination rate, and compatible herbicides. Suited for full sun to partial shade, it is a vigorous plant when grown in wet to mildly wet soil, either fertile clay or loam and preferably slightly acid. Flowers bloom from early September through early November. The stalk dies in the middle of October and is reasonably dried by the first of December.

Stem construction consists of a waxy epidermis with xylem cylinder and spongy pith with a "pinhole" tube at the center. The xylem/pith radius ratio (*XPR*) is about 0.46 and typical stem diameter is 0.95 cm. Typical stalk weight is 26 g, height is 130 cm, and cultivation density is $72/m^2$. The density of the aster woody material (xylem) was determined to be $474 kg/m^3$, which is similar to that of a light hardwood (lighter than pine).

New England Aster is probably the latest maturing of the SSPs. This could be an important factor in extending the harvest season.

Fig. 3. Kinghead Ambrosia growing within corn crop.

Kinghead Ambrosia (Asteracea Ambrosia trifida) *(Fig 3)*

Kinghead Ambrosia is a wildflower, but the flower color is green, and therefore it is not recognizable in the field as such. Definitely considered a "weed" by farmers and woodsmen alike, it lines ditch banks and invades cornfields with equal vigor. It is a floodplain species but does well also in moderately wet fields. The plant height is amazingly impressive, easily exceeding 3 m and sometimes reaching 5 m.

Kinghead Ambrosia is an annual but drops sufficient seed (up to 275/ plant) to ensure its steady existence. Pollination occurs in mid-July. Pollen is very small and easily windborne, making it an allergen for humans, although not as serious as its related Common Ambrosia. Seeds are 0.3 to 0.5 mm long, with a woody hull bearing blunt ridges that end in several short, thick spines at the tip. They germinate after a cold, moist dormant period. The stem has extended branches primarily at its top and grows thick enough to make a canopy to maximize its absorption of solar radiation. The stalk dies in late September or early October and dries down quickly (typically 2 wk).

Stem construction consists of a porous epidermis (not waxy), which probably is the cause of its quick drydown. The xylem cylinder has an *XPR* of 0.23, and a typical stalk diameter of 1.6 cm. Xylem material has a density of about 240 kg/m^3, which makes it one of the lightest materials of all the SSPs introduced here. The pith is a solid spongy inner core that rots after about 2 mo of drydown.

Kinghead Ambrosia was suggested as an energy fuel more than 10 yr ago *(6)*. Yields on the order of 2.5 t/acre were quoted. In the analysis done here, I find this number a gross understatement and project yields of 13.4 t/acre without adaptation or modification of the plant as it currently exists.

Kinghead Ambrosia is the largest plant on the list of SSPs, in both height and stem diameter. Although this corresponds to a great bulk of material from this plant, it does not generate a tremendous weight because of its relatively low density. However, the pollen from this plant is very small and easily airborne, causing allergies in humans. Before this plant could be cultivated commercially, it probably would need some alteration.

Evening Primrose (Onagracea Oenothera)

Evening Primrose is a biannual wildflower named for its habit of opening yellow blossoms at dusk. The four-petaled flowers are strongly scented with a sweet perfume that attracts pollinating moths. Evening Primrose is easily cultivated; it prefers acid, neutral, or alkaline, well-drained soils and requires full sun. It does best when not having to compete for soil or space.

Because the Evening Primrose is a biannual, the stem shoots up only in the second year of growth. In the first year, a taproot is put down. In the second year a sprout shoots up. Producing a biomass material only every other year is a definite drawback to its use as a biofuel; however, the density of its xylem material is significantly greater than that of the other candidate plants, actually giving the evening primrose a competitive output.

Evening primrose is grown commercially for its seed oil (treats asthma, arthritis, headaches). Consequently, there is a great bed of knowledge concerning its seed production, cultivation, and even some insights into strategies for making it provide an annual shoot.

Stem construction consists of a thin, barklike epidermis. The xylem cylinder has an *XPR* of 1.3 and a typical stalk diameter of 1.5 cm. Xylem material has a density of about 536 kg/m^3, which makes it almost comparable to hardwood. The pith is a solid spongy inner core that rots after about 2 mo of drydown.

Evening primrose has a dense "stem," probably indicating a high percentage of lignin, and a correspondingly higher heating value than the other SSPs. Being a biannual is a mixed bag. The harvest is less frequent, which is an advantage, but the population density of harvestable plants is only half of what an annual or perennial would be.

Horseweed (Asteracea Conyza canaensis)

Horseweed is a native annual plant that can grow to a height of over 2 m. When mature, several flowering stems appear at the apex, which branch frequently and create a multitude of tiny composite flowers. In each flower, there are numerous yellow disk florets in the center, which are surrounded by tiny white ray florets. There is no noticeable floral scent. The blooming period can occur any time from midsummer to fall, lasting about 3 wk.

Table 1
Physical Properties of SSP

Plant	Stalk diameter (cm)	XPR	Average height (cm)	Material density (kg/m^3)[a]	Growth density (stalks/m^2)	Projected yield (mg/ha[t/acre])[b]
New England Aster	0.85	0.46	127	593	55	19.9 (7.8)
Kinghead Ambrosia	1.25	0.23	180	394	46	29.8 (13.4)
Evening Primrose	1.27	1.31	175	748	28	17.1 (7.5)
Horseweed	0.9	0.92	160	675	55	30.4 (13.3)
Cockleburr	1.3	0.46	145	390	14	4.6 (2)
Field Thistle	2.0	0.76	190	425	11	7.3 (3.2)
Dames Rocket	1.1	0.22	110	345	26	2.7 (1.2)
Goldenrod	0.8	0.78	135	694	75	21.2 (9.3)
Annual Sunflower	1.1	0.46	170	784	40	19.5 (8.5)

[a] Measured by sampling of stalks, mass was measured by scale, and volume by stalk diameter, XPR, and length.

[b] Density × avg stalk height × cross section of xylem cylinder × growth density × hectare conversion factor.

The leaves alternate all around the stem (appearing almost whorled) and differ little in length, creating a columnar effect. The stout central stem is ridged and unbranched, except for the flower stems near the apex. Seeds are tiny and distribution is by wind. The preference of the plant is full sun, moist to dry conditions, and rich fertile soil. However, this plant flourishes in other kinds of soil, including those containing considerable amounts of gravel and clay. This weedy plant is easy to grow and sometimes forms large colonies in favorable disturbed sites. Drought resistance is very good. The plant dies in early September and drydown is rapid.

Stem construction consists of a moderately waxy epidermis. The xylem cylinder has a *XPR* of 0.92 and a typical stalk diameter of 0.9 cm. The xylem material has a density of almost 675 kg/m^3, which is a little light. The pith is a solid spongy inner core that appears to be resilient to rot for many months.

According to estimates, horseweed may have one of the highest yields of all the plants presented here (*see* Table 1). Projections indicate that 13.3 t/acre can be taken with current cultivation techniques and no engineering of the plant. Another benefit of horseweed is that it flourishes in dry conditions and in rough soil such as clay and gravel. It is also an early maturing plant and can be harvested as a fuel as early as September.

Cockleburr (Asteraceae Xanthium strumarium)

The cockleburr is a hitchhiker. The seed pod is a burr with hooked spines. It tangles the fur of animals unfortunate enough to brush against the dying plant.

Male flower heads occur at the ends of branches, and the female flower heads occur in the lower parts of these branches. The female heads develop into hard, woody, spiny burrs. These burrs are oval shaped, brown, 20–30 mm long, and covered in hooked spines.

Cockleburr is an annual species that generally germinates from late winter to late summer. Germination often occurs after rainfall and irrigation. The burrs contain two seeds, one larger than the other. The larger seed has limited dormancy and usually germinates in the season it is produced or the following season. The smaller seed has a longer period of dormancy. The plant grows in a wide range of soil types.

Stem construction consists of a moderately waxy, dark brownish-red epidermis. The xylem cylinder has an *XPR* of 0.46 and a typical stalk diameter of 1.75 cm. Xylem material has a density of almost 390 kg/m^3, which corresponds to a corkwood. The pith is a solid spongy inner core that appears to be resilient to rot for many months.

Although an SSP, cocklebur does not have good technical characteristics. In particular, the low *XPR* and density indicate that there is not much dry matter in this stalk. In addition, the burrs are a hazard, or at least an inconvenience, to the workers who must deal with this material. Surely the most serious disadvantage is that it is rated a Class C noxious weed, indicating that the introduction of burrs must be prevented.

Field thistle (Asteraceae Cirsium discolor)

Field thistle is a robust annual and member of the sunflower family. It grows to monster proportions (easily 2 m) with good soil and proper moisture. Flowering heads bear elongated, purple to lavender disk flowers that bloom in July and August. Leaves emerge individually along the entire stem. Leaf margins, the tips of leaf lobes, and parts of the stem all bear spines. The plant dies off in early September and dries down to low moisture content within four weeks.

One plant has the potential to produce up to 5200 seeds in a season, but the average seed production is about 1500 seeds per plant. Seeds are dispersed primarily by wind.

Thistle grows in a wide variety of soils, including sand dunes, but it is most abundant in clay soils. It can tolerate saline soils and wet or dry soils, but it grows best in dry soils. There are many other varieties, including Canadian and Bull.

In large thistle plants, the stem can be 3 cm in diameter. Although this stem size is admirable from the prospect of bulk, it may make cutting by conventional cutter-baler equipment difficult. The stalk consists of a large, spongy pith that does not rot or dry up for up to 1 yr. Although the stem diameter is impressive, the density of burnable mass is only moderate and the expected yield/acre is low.

Although thistle does thrive in sandy soil, most varieties of thistle are highly competitive and in some areas are classified as a noxious weed. It is also referred to as a "highly disruptive exotic plant."

Fig. 4. Field of mixed plants but mostly goldenrod and New England Aster.

Dames Rocket (Cruciferae Hesperis matronalis)

Dames Rocket is a showy, spring perennial wildflower with large, loose clusters of fragrant white, pink, or purple flowers that bloom in April and May on flowering stalks about 1 m high. This member of the mustard family has flowers with four petals. Many seeds are produced in long, narrow fruits. The leaves are oblong, sharply toothed, and alternately arranged. Leaves decrease in size as they ascend the stem.

This plant usually grows in moist soil and does best in sun conditions. The seed is commercially available since it is often planted ornamentally and included in many wildflower seed mixes.

Dames Rocket dies off and dries out by early August. It is one of the earliest of the sclerified stalked plants that is ready to harvest. The plant grows to over 1 m, and the stem diameter is about 1.1 cm. The *XPR* for this plant is a lowly 0.22, with a correspondingly low expected yield.

Goldenrod (Asteraceae Solidago) *(Fig. 4)*

Goldenrod is a perennial wildflower with a multitude of varieties. It is the state flower of Alabama, Nebraska, and Kentucky. Most species have feathery, rich sprays of florets atop sturdy stems. These small clusters of yellow flowers are prominent features of the landscape in September and October, and signal the end of summer. Goldenrod blooms late and dries down slowly, probably owing to the protective waxy epidermis of its stem.

Goldenrod is an erect perennial with simple, alternate, toothed or smooth-margined leaves. Its dried leaves have been used for a tealike beverage by the Indians.

There are many varieties, including early and Canadian. All enjoy full sun and a variety of soil conditions. In general, they present no difficulties in growing. The plant propagates itself by both a spreading root system and seed.

Fig. 5. Wild sunflower is much different from domestic sunflower.

It can grow to 2 m with a stalk that is about 0.8 cm in diameter. In the stem cylinder, the XPR is 0.78 and it has a density that rates well.

Some varieties of late goldenrod (Canadian) are late blooming and even later drying down, so they may not be ready for harvest until almost December. There is a misperception that goldenrod causes hay fever; it is actually the pollen of ragweed and grasses that causes this. Goldenrod's pollen grains are relatively large, heavier than air, and therefore are carried off by flies, bees, butterflies, even ants or birds, but not by the wind.

Annual Sunflower (Asteraceae Helianthus) *(Fig. 5)*

To most people, sunflower conjures an image of a domestic plant with a large stalk crowned by a single large flower. The wild sunflower, or annual sunflower, however, exhibits a branched growing form with numerous smaller flowers at each branch tip. The average diameter of wild sunflower is about 1 cm, unlike cultivated forms, which commonly reach 30 cm.

The stem is erect, columnar at the base and branched at the top. The leaves are alternate, simple, rough, hairy, and ovate or heart-shaped with toothed edges. The heads are showy, with yellow to orange-yellow ray flowers and brown or dark reddish-brown disk flowers. Sunflowers begin to grow in early June, flower in August and September, and mature seed and die in late September.

Wild sunflower, or common sunflower, is an annual, reproducing by seed. The seeds are shaped like the commercial sunflower seeds bought in stores, but much smaller and spread by the wind.

These plants can grow to 3 m with a stalk that is about 1.1 cm in diameter. Stem construction consists of a moderately waxy, dark red epidermis. The xylem cylinder has an XPR of 0.46. Xylem material has a density of 540 kg/m^3, which is about half that of pine wood. The pith is a solid spongy inner core that appears to be resilient to rot for many months.

Methods

Table 1 is important to the analysis of SSPs because it establishes a basis for future evaluation of the fuel source. Yet, much of the information is subject to growing conditions such as soil, water, and amount of competition with other plants. Because there are no cultivated acres of these plants, the projected yields listed in Table 1 are based on stalk weights, which were measured, and growth density ($stalks/m^2$), which were estimated. The estimations came from grid layouts made in productive parcels of wild-grown fields. They represent what I feel to be a conservative estimate of what densities can be achieved in cultivation.

The material density was determined from stalk weight and *XPR* based on the assumption that the stalk is a composite material of hard biomass and soft pith. The weight, but not the volume, of the pith was neglected:

$$\text{Density} = \text{Avg stalk weight} / \begin{matrix}(\text{avg stalk height} \times \text{cross-sectional area} \\ \text{of stalk} - \text{cross-sectional area of pith})\end{matrix}$$

Projected yield (PY) was determined using the following formula:

$$\text{PY} = (\text{density} \times \text{biomass stalk volume} \times \text{no. of stalks/acre})$$

$$\text{PY (t/acre)} = \text{Mat density} \times \text{Avg Stalk Height} \times \pi \times \text{diam}^2 (1 - 1/XPR^2)/4\ /2.2/2000$$

Analysis

It is not the objective of this article to analyze the plants in the set of SSPs to determine which would be the most acceptable as an energy crop. One reason for this is that SSPs, as a fuel source, are a variety of plants rather than just one. As a variety, they have much more flexibility. It is expected that power plants fueled by SSPs will actually have farm contracts for several of the species within the set. Some species will be harvested and delivered early in the season and others late. This facilitates the storage of the fuel since the window of harvest can be up to 6 mo.

In addition, some SSPs dry down better than others. Having a variety of moisture conditions may be of benefit to the burner. Burning some green material with fully dried material is often the best solution for determining burner feed rates and utilizing the full combustion chamber.

Another reason for keeping all the varieties in the SSP set is that some grow better in certain soils and climates. This is not to say that the nine species identified here will all be viable energy crops, or that other species will not be added. For example, it is hard to imagine any farmer wanting to work with field thistle, no matter how much protective clothing the farmer has. Yet, thistle shows some signs of having the capability of delivering high yield, and, therefore, it should stay a member of the list awaiting further research.

Cocklebur may not be an acceptable member because it is a Class C noxious weed in many parts of the United States. Couple this with the fact that it does not have good physical characteristics for a biofuel and cockleburrís place on the SSP list is precarious.

Some may argue that Evening Primrose is not a true candidate owing to its biannual nature. However, its SSP harvestable material is the densest of all the members of the list, as if the additional year that it takes to mature may have been well spent. More research is needed to determine the density at which it can be planted, and what effect the first-yr plant will have in occupying space in the field.

A further argument for keeping active all members of the SSP list is that there is some interest in targeting acreage that is currently in government "set-aside" programs as sources of the biomass material. In this case, without preparation of the field, the herbaceous stalked material may simply grow wild on the acreage. If this is to be the case, it may not be possible to select the actual plants that will be harvested, and they may include all members of the list along with grasses and more.

It is also not the objective of this article to compare SSPs as a biofuel crop against other energy crops that are currently under research. The primary reason for this is that there is no competition among energy crops. If biofuel is to become significant in the mix of energy sources, all biofuels will need to be collected. In fact, it can be imagined that if a power plant is built to burn biofuels, it may well prefer a proper mix of woody and herbaceous materials along with quantities of animal waste.

However, to demonstrate that SSPs deserve their place in the mix of energy crops, one comparison with other biofuel crops should be made. Table 1 gives the physical characteristics of the nine plants in the SSP set. Of particular importance in Table 1 is the last column, which represents the projected yield of each (in t/acre).

With this caveat, Table 1 indicates that the highest yields are >10 dry t/acre. This compares to corn stover at 2.8 t/acre *(8)*, switchgrass at 2.5 t/acre *(9)*, and willow seedling at 6 t/acre/annum *(10)*. Figure 6 puts Table 1 to life, showing the cross sections of each of the SSPs discussed.

Conclusion

SSPs have been introduced as a group of herbaceous plants that should be given recognition as a biofuel feedstock. They should be given their

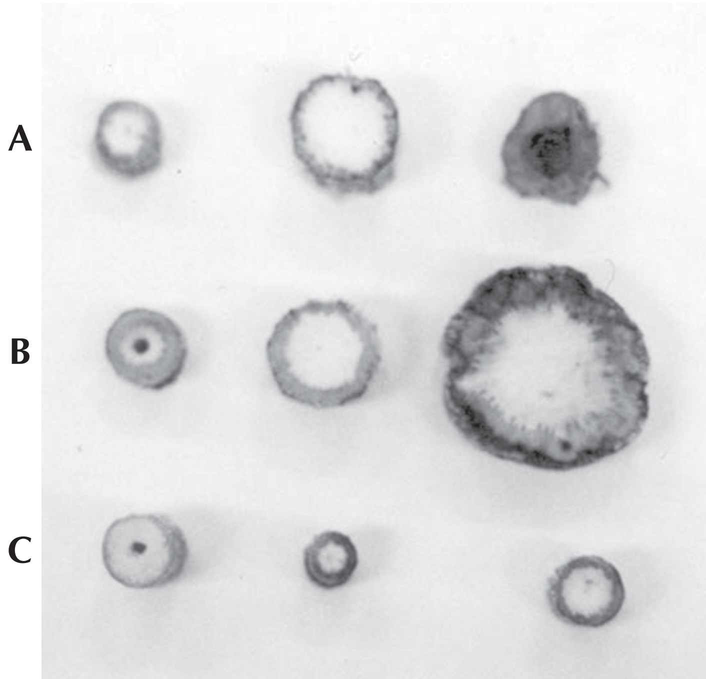

Fig. 6. Cross sections of SSPs, to scale (left to right): **(A)** New England Aster, Ambrosia Kinghead, evening primrose; **(B)** horseweed, cockleburr, thistle; **(C)** Dames Rocket, goldenrod, sunflower.

place in the development of renewable biomass material for direct energy conversion ("directly burnable crop" *[11]*).

In this article, this new energy crop has been introduced and its benefits extolled, in particular, the yield data of Table 1. However, the specifics were done within the economic and time constraints of the grant and are left open for more detailed scrutiny. In particular, the botany and plant physiology of the SSPs need clarification by experts, as do the physical characteristics of Table 1. Further studies are needed to establish heating values for the SSPs and to determine combustion characteristics. Knowledge of the cultivation and harvest of these plants must be expanded. The hope is, however, that the set of plants discussed here makes direct burnable biomass an economically feasible alternative on a broad scale.

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