# Potential New Bioenergy and Bioproduct Crops

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Walsh, M.E. (2007, February). Potential new bioenergy and bioproduct crops. Sun Grant BioWeb. Retrieved from http://bioweb.sungrant.org

Agricultural and forestry resources that have been the traditional sources of raw materials for bioenergy and bioproducts will continue to play a major role in the emerging biobased industry. However, a number of new crops are currently being examined as potential feedstocks. The new crops being explored include oilseeds, rubber/resin crops, non-wood fiber crops, herbaceous grasses, and fast growing wood crops. The new oil seed crops and rubber/resin crops are of interest because of the unique chemical compounds they produce, which provide different performance characteristics than many of their existing (petroleum derived) counterparts. Some can also be potential sources for biodiesel. The new fiber and short rotation wood crops can be used as new sources for traditional fiber uses as well as new composite materials, but because of their high biomass production and fast growth characteristics, they also could become cellulose feedstocks for bioenergy and bioproducts. The herbaceous grasses can be used as forage crops for livestock, but are also being developed as cellulose feedstocks.

The list of new bioenergy and bioproduct crops that could be potentially developed is large. In 1956, the U.S. Department of Agriculture undertook a systematic effort to identify potential new crops which could be produced in the U.S., many with industrial applications. Several promising candidates were identified. Since then, research has been conducted on a number of these crops. Resources devoted to this effort have been limited and often sporadic, resulting in stops and starts. Therefore, the crops described in this section are either not yet being commercially produced, or are so only on small numbers of acres. However, these crops have received sufficient research and development efforts (both genetic and agronomic) to be realistic candidates for near term (over the next decade) commercialization, at least at a regional level. The list is not exhaustive, but rather provides a flavor of the breadth of new crops that could become commercial bioenergy and bioproduct crops.

## Oilseeds

In addition to traditional food and feed uses, many oilseed crops currently produced in the U.S. (e.g. soybeans, sunflowers, and flax) are used to produce bioproducts such as lubricants, adhesives, components of plastics, degradable inks, paint additives, and detergent surfactants, among other uses. The growing biodiesel market offers the potential for large-scale use of oilseed crops. In addition, the U.S. imports oils such as palm oil and castor oil for industrial use. In 1956, the U.S. Department of Agriculture undertook a systematic effort to identify potential new crops (many with industrial applications), which could be produced in the U.S.  A large number of oilseed crops were identified as potential candidates, due largely to their unusual fatty acid compositions. These traits can confer different performance characteristics and potentially provide an improved environmental footprint, relative to petroleum-derived counterparts. The new crops also offer added crop production options for farmers and can potentially create new rural jobs when used for industrial products. The list of potential new oilseed crops that can be produced is long. Among some of the more promising crops are rapeseed (both industrial varieties and canola varieties), *Castor*, *Crambe*, *Cuphea*, *Lesquerella*, meadowfoam, *Vernonia*, *Euphorbia*, *Stokesia*, *Camelina*, and *Jojoba.*

## Industrial Rapeseed

Rapeseed is a generic term for a number of different species which are similar in appearance, but sometimes substantially different in chemical composition or botanical origin. Rapeseeds are members of the *Brassica* family which also includes broccoli, cabbage, cauliflower, mustards, etc. Most rapeseed produced today is Canola, a variety of rapeseed with low glucosinolate and low erucic acid content, suitable for human consumption. However, varieties of rapeseed that contain high levels of the fatty acid erucic acid in the oil are produced as an industrial crop. Industrial uses of erucic acid include lubricants, plasticizers, coatings, surfactants, and rubber additives.

Industrial rapeseed is a cool season annual and includes both winter and spring varieties. The most common species commercially grown in the U.S. are *Brassica napus* (a winter variety) and *Brassica campestris* (a spring variety). It can be grown throughout much of the United States wherever wheat is grown, but varieties suitable for efficient commercial production are lacking for many areas.
Winter varieties need to be planted early enough to reach a rosette size of 6 to 8 leaves before the first hard frost, which generally occurs between mid-August and mid-September, depending on geographic region (earlier in the northwest and later in the southeast). Harvest is generally in late May to early July, again depending on geographic

region. Spring rapeseed is generally planted in March-April and harvested in August-September. Rapeseed requires a firm seed bed and a relatively shallow planting depth. Fairly narrow row spacing (6-12 inches) is recommended. Seeding rates of 4-8 lbs/ac are typical if planting is by grain drill (higher rates are needed for broadcast planting).

Winter rapeseed varieties can generally be grown in the same regions where winter wheat is grown, but are generally planted 2 to 4 weeks earlier than winter wheat. Compared to winter wheat, rapeseed is more tolerant of drought and saline conditions. Rapeseed does not tolerate wet soils. The nutrient requirements of rapeseed are similar to other small grains (e.g., 80-100 lbs N/ac, 30-40 lbs $P_2O_5$/ac, and 60-80 lbs $K_2O$/ac). Sulfur may also be necessary, particularly in sandy soils. Rapeseed is ready to harvest when the seeds have dried to 10% moisture. A moisture content of 8% is recommended for long term seed storage. Rapeseed is susceptible to pathogens that can rapidly build up in the soil and should be produced in rotation with other non-*Brassica* crops, planted once in a 3 or 4 year period. Production of rapeseed uses the same equipment (with some adjustments to accommodate the small seed size: 90,000 to 150,000 seeds/lb) used to produce small grains (i.e., wheat, oats, barley, etc.). Production costs are similar to those of wheat.

Seed yields show substantial regional variation, largely due to the lack of appropriate varieties. Yields have been highest in the Northwest. Average commercial yields of about 1,300 to 1,500 lbs seed/ac are typical. Oil constitutes 40-45% of the seed weight and erucic acid is 45-50% of the oil. The meal is characterized by a high concentration of glucosinolates, which decreases the palatability of the meal to livestock and can be toxic to some animals, limiting its usefulness as a livestock feed.

Commercial production of industrial rapeseed in the U.S. is limited (Table 1, page 4). Most is produced in the Northwest in regulated rapeseed production districts due to the potential to cross-pollinate with other *Brassica* species.

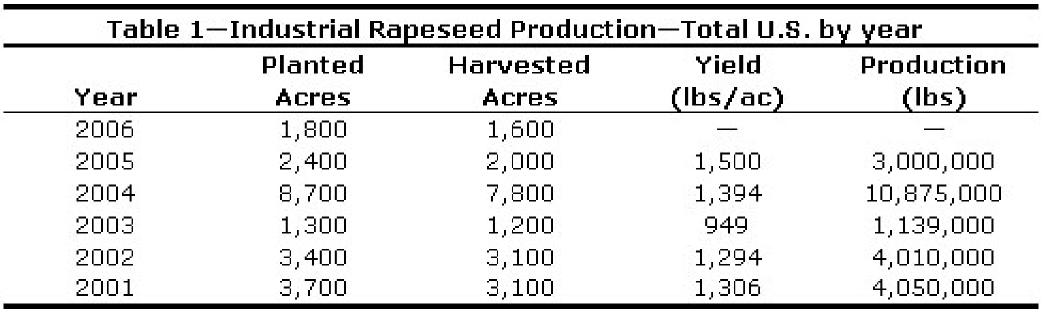

Table 1—Industrial Rapeseed Production—Total U.S. by year

| Year | Planted Acres | Harvested Acres | Yield (lbs/ac) | Production (lbs) |
|---|---|---|---|---|
| 2006 | 1,800 | 1,600 | — | — |
| 2005 | 2,400 | 2,000 | 1,500 | 3,000,000 |
| 2004 | 8,700 | 7,800 | 1,394 | 10,875,000 |
| 2003 | 1,300 | 1,200 | 949 | 1,139,000 |
| 2002 | 3,400 | 3,100 | 1,294 | 4,010,000 |
| 2001 | 3,700 | 3,100 | 1,306 | 4,050,000 |

Source: U.S. Department of Agriculture, National Agricultural Statistical Service

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## Canola

Canola is an edible rapeseed variety that has been bred to contain less than 2% erucic acid in the oil and less than 30 micromoles of glucosinolates per gram of oil free meal. Both *Brassica napus* and *Brassica rapa* varieties have been commercially produced, but in recent years *B. napus* varieties have come to dominate production in North America. Canola quality seed has also been developed in *Brassica juncea* (brown mustard) and commercial production of these varieties is just beginning. Canola seeds are approximately 40% oil consisting mostly of poly-unsaturated fatty acids, with about 6% saturated fat. Canola meal is approximately 34-38% protein and is complementary to soybean oil meal. It is often mixed with soybean meal in feed rations (10-20% of the total ration). About one million acres of canola are produced annually in the U.S., with most production in South Dakota and Minnesota (Table 1, page 5). It is produced almost entirely for food uses as a healthier alternative to other vegetable oils. Grading standards for canola oil have been established by the U.S. Department of Agriculture Grain Inspection Service. However, the low level of saturated fat in canola oil is also a desirable characteristic for biodiesel production, as it provides improved cold flow properties. Interest in using canola as a biodiesel feedstock is increasing. In 2006, construction of two biodiesel plants using canola began in North Dakota, with announced plans for additional plants in other parts of the U.S. and Canada.

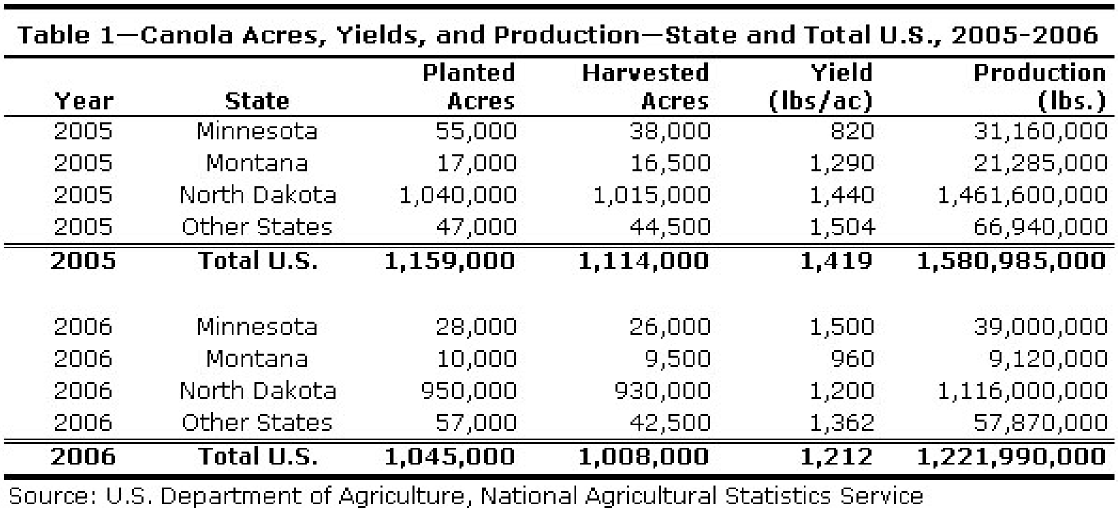

**Table 1—Canola Acres, Yields, and Production—State and Total U.S., 2005-2006**

| Year | State | Planted Acres | Harvested Acres | Yield (lbs/ac) | Production (lbs.) |
|---|---|---|---|---|---|
| 2005 | Minnesota | 55,000 | 38,000 | 820 | 31,160,000 |
| 2005 | Montana | 17,000 | 16,500 | 1,290 | 21,285,000 |
| 2005 | North Dakota | 1,040,000 | 1,015,000 | 1,440 | 1,461,600,000 |
| 2005 | Other States | 47,000 | 44,500 | 1,504 | 66,940,000 |
| **2005** | **Total U.S.** | **1,159,000** | **1,114,000** | **1,419** | **1,580,985,000** |
| 2006 | Minnesota | 28,000 | 26,000 | 1,500 | 39,000,000 |
| 2006 | Montana | 10,000 | 9,500 | 960 | 9,120,000 |
| 2006 | North Dakota | 950,000 | 930,000 | 1,200 | 1,116,000,000 |
| 2006 | Other States | 57,000 | 42,500 | 1,362 | 57,870,000 |
| **2006** | **Total U.S.** | **1,045,000** | **1,008,000** | **1,212** | **1,221,990,000** |

Source: U.S. Department of Agriculture, National Agricultural Statistics Service

Nearly all of the canola currently produced in the U.S. are spring varieties. Spring canola varieties are planted in the spring, when weather and soil conditions permit, which is generally in late April to mid-May in the northern states. Soil temperatures should have warmed to 45 to 50°F before planting. Spring canola varieties generally take 95 to 100 days to mature. Winter canola varieties (varieties planted in the fall and harvested the next spring/summer) frequently do not survive the cold winters experienced in the northern states. However, efforts are underway to develop winter varieties for other parts of the country, most notably the Southern Plains (as a joint effort between Kansas State University and Oklahoma State University in the public sector, and some private seed companies). Winter canola should be planted six weeks prior to the typical first killing frost date for the area. The U.S. Canola Association reports that 60,000 acres of winter canola were planted in Kansas and Oklahoma for the 2006 crop year.

Interest in winter canola is being spurred not only by the potential for new markets, but also by the need to develop a crop that can be produced in rotation with winter wheat. Substantial winter wheat production in the Plains states is produced as a continuous monoculture and suffers from insect, disease, and grass seed contamination problems as a result. Attempts to introduce summer crops (such as soybeans, corn, and sorghum) into wheat production systems in these areas have had limited success, due to dry conditions. Winter canola production is compatible with winter wheat production; planting and harvest dates are similar and use much of the same equipment, thus it may be a viable option as a rotational crop. Winter canola yields are somewhat less than winter wheat and per bushel weights are lower (50 lbs/bu compared to 60 lbs/bu for wheat), but prices are generally higher. However, yields of winter wheat following canola production are reported to be 8-20% higher than in continuous winter wheat systems, depending on location. Winter survival rates are key to the successful production of canola in the Southern Plains.

Attempts to expand the range of canola production beyond the North and South Plains are also underway, although more limited. In particular, canola is being examined as a potential crop in double cropped systems that currently use winter wheat. Compared with winter wheat, canola matures a little earlier (7-10 days) which permits earlier planting of the second crop, and canola leaves fewer residues on the field, making no-till planting of the second crop a more viable option.

Canola grows best in medium-textured, well-drained soils, but can be grown in a wide variety of soils. Soil pH between 6 and 7 is optimal and yields may be significantly reduced in soils with a pH of less than 5.5. It does not tolerate waterlogged or poorly drained conditions. Seedlings are susceptible to many herbicides (particularly sulfonylureas widely used in wheat production), and carryover residues of these herbicides in the soil, or in herbicide application equipment, can be problematic. Herbicide resistant varieties (to glyphosate, glufosinate, and imidazolinone) have been developed. The seedbed needs to be fairly level and firm, and planting depths should be between 0.5 and 1 inch. No-till production is possible, but results have been mixed. However, no-till production is recommended for soils with lower initial moisture levels. Seeding rate recommendations range from 4 to 10 lbs/ac. The wide range of seeding rates is in part due to the differences in seed size among canola varieties. For *B. napus* varieties, seed numbers per pound range from 75,000 to 160,000.

Recommended row spacing is around 6-7.5 inches apart although wider spacings (up to 15 inches) are being explored. A plant density of 10-16 plants/ square foot is considered good to ideal and a density of 4 plants/ square foot is the minimal requirement for a viable stand.

Recommended nitrogen rates depend on expected yields and whether the variety planted is an open-pollinated variety or a hybrid (or synthetic) variety. For open pollinated varieties, 65, 100, and 130 lbs N/ac are recommended for yields of 1,000, 1,500, and 2,000 lb/ac respectively. For hybrid and synthetic varieties, recommended levels are 15-20 lbs N/ac less for each expected yield level. For winter canola varieties, nitrogen is applied in a split treatment (about 1/4 to 1/3 of the total applied in the fall and the remainder in the spring). Fall application of phosphorus has also improved the winter survival rate on some soils. Recommended levels are 20-30 lbs $P_2O_5$/ac on soils with medium available phosphorus levels and up to 45 lbs $P_2O_5$/ac on soils with low available phosphorus levels. Potassium should be added if soil tests indicate low levels. Additionally, on some soils, canola has been responsive to the addition of sulfur (10-30 lbs S/ac, depending on existing soil levels).

Canola harvest can either be by swathing and then combining (most typical in spring canola varieties) or direct combining (recommended for winter varieties and increasingly being used with spring varieties). If swathing is used, the crop should be cut when 20-30% of the seeds on the main stem have turned from green to brown. The seeds will be about 35% moisture at this time. Swathing should be done just below the lowest seed pods, leaving the stubble as high as possible. Combining (either direct of in combination with swathing) should occur when the average seed moisture is 8-10% and no green seeds are visible. Delayed harvesting can result in significant yield losses due to the seed pods splitting and spilling the seeds on the ground (seed shattering).

Among the most serious diseases that affect canola are blackleg (*Leptosphaeria maculans*), Sclerotinia stem rot (*Sclerotiorum sclerotiorum*), powdery mildew (*Erysiphe cruciderarum*), Alternaria black spot (*Alternaria* spp.) and aster yellows. Growing canola in 3-4 year rotations, or avoiding planting in rotation with crops that are also hosts to a disease (such as soybeans and sunflowers for sclerotinia) can help reduce the incidence of disease. A number of insects can damage canola. Among the most damaging are flea beetles (*Phyllotreta* spp.) and aphids (*Brevicoryne* spp.). Spring canola varieties are more susceptible to flea beetles than are winter varieties, due to the later emergence of spring varieties compared with winter varieties.

Canola yields vary substantially from site to site and from year to year, largely due to variations in weather as occurs with all crops (Table 1). Additional issues associated with commercial production of new crops are the lack of suitable varieties appropriate for a wide range of soil and weather conditions, and the need to refine crop management recommendations. To address these issues, the national winter canola variety trials (initiated in the 1994-1995 growing season and coordinated by Kansas State University) evaluate released varieties, experimental varieties, and herbicide tolerant varieties at several locations in 21 states in the Great Plains, Midwest, and Southeast.

Winter varieties generally average higher yields than do spring varieties (as much as 30-35% higher). For example, potential yields of spring canola in Michigan are estimated to 1,500 to 2,500 lbs/ac and 2,000 to 3,000 lbs/ac for winter canola. In Idaho, Washington, and Oregon, five year average yields of winter canola have been 3,240 lbs/ac and 1,683 lbs/ac for spring canola. Winter canola varieties have averaged 1,500 lbs/ac in Okalahoma and have been as high as 2,000 lbs/ac.

The cost of producing canola is similar to winter wheat. Data collected from commercial canola production in southeastern North Dakota from 1995 to 1998 report a gross income ranging from $135.73 to $186.88/ac. Average yields for the period were 1,311 lbs/ac and average price was $11.87/cwt. The average production cost was $117.63/ac ($113.64/ac for variable costs and the remainder for fixed costs). Analysis estimated the yields of conventional and Round-Up Ready® Winter Canola that would be needed to provide the same income as winter wheat in Oklahoma. Data indicated that at prices of $3.00/bushel for wheat and $0.08/lb for canola, conventional canola yields of 1,471, 2,005, and 2,540 lbs/ac would be required to break even with wheat yields of 30, 45, and 60 bushels/ac respectively. Corresponding yields for Round-Up Ready® canola are 1,609, 2,143, and 2,677 lbs/ac. The analysis did not include any benefits that may accrue (due to the impact of crop rotations) on changes in wheat inputs and yields, but did include the value of government support payments (the 2005 national loan rate of $2.75/bu for wheat and $0.093/lb for canola). Canola is eligible for loan deficiency program payments under the USDA administered commodity programs. Analysis of the spring canola yields needed to cover total production costs (variable costs, producer's own labor, machine cost, and a land rental cost; $2006 - under dry land production conditions in eastern Washington for several rainfall and canola oil price scenarios) ranged from 700 lbs seed/ac at an oil price of $0.203/lb and 12-15 inches of rainfall to 2000 lbs/ac at an oil price of $0.10/lb and more than 20 inches of rainfall.

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## Castor

Castor bean (*Ricinus communis*), a member of the spurge family, is a semitropical plant thought to be native to Africa. The seeds contain 35-55% oil and contain hydroxyl fatty acids, which are used to make high quality lubricants for heavy equipment or jet engines. The seeds, leaves, and stems (but not the oil) contain ricin and ricinine, chemicals that are highly toxic to humans and animals. The plant is also allergenic. Castor beans were produced in the southern United States until the 1970s, but production was discontinued due to its toxicity and allergenicity. The U.S. annually imports about 41,000 metric tons of castor oil from Brazil and India at a cost of around $100 million. The world market for castor bean oil is estimated to be 1 billion pounds annually.

In the tropics, castor bean is a perennial and can grow to 30-40 feet tall. It is grown as an annual in temperate regions and generally grows to 4 or 5 feet tall. The growing season is 140-180 days and germination is slow (10-21 days after planting). Potential production regions in the U.S. include southeastern Kansas, Missouri, southern Illinois and Indiana, Tennessee, Kentucky, and parts of Oklahoma and Texas.

Castor beans are planted in early May on disked or plowed sites at a depth of 1.5 to 3 inches. Seeding density is 10-14 lbs/ac. Castor beans are planted at row widths of 38-40 inches and within row spacing of 8-12 inches. Nitrogen application rates depends on soil organic matter with higher nitrogen (up to 100 lbs N/ac) required on sites with little organic matter (less than 2%) and lower rates (about 40 lbs N/ac) on sites with high organic matter (greater than 10%). Approximately 20 lbs $P_2O_5$/ac and 40 lbs $K_2O$/ac are applied on soils with high phosphorus and potassium levels (i.e. 6-10 ppm P; 81-100 ppm K). Higher levels (5 lbs $P_2O_5$ and 20-30 lbs $K_2O$/ac) should be applied for soils low in P and K. Excessive application of phosphorus can reduce yields.

Due to its slow emergence, castor beans are not competitive with weeds and so weed control is essential. Harvest is annually and should begin within two weeks following the first killing frost. Combines should be adjusted to account for the tendency of castor beans to crack during harvest. Seed yields of 2,200 lbs/ac have been achieved in the U.S. tests.

Attempts to rid castor from ricin and allergens using traditional breeding methods have been unsuccessful. However, the USDA Agricultural Research Service reports the successful development of low toxic and allergenic varieties using biotechnology methods (i.e., development of antisense genes) to block the production of these compounds, thus enhancing the potential for castor beans to be once again produced in the United States.

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## Crambe

*Crambe* (*Crambe abyssinicia* Hochst), also called Abyssinian mustard, Abyssinian kale, colewart, or katran, is a member of the mustard family (Cruciferae) and is native to the Mediterranean region. *Crambe* is an erect annual herb and is relatively drought tolerant. *Crambe* seeds contain 28-33% oil, of which 50-60% is erucic acid. *Crambe* oil also contains oleic acid (around 17%) and linoleic acid (about 9%) as well as linolenic and eicodenoic acid. Erucic acid is used in a number of industrial applications including plastic films, lubricants, and surfactants. The current primary source of industrial erucic acid is industrial rapeseed.

Research has focused on developing *Crambe* for production in the Midwest, Pacific Northwest, and Southwest U.S. Limited (up to about 58,000 acres) commercial production of *Crambe* occurs in North Dakota, where it is a cool season crop. It is planted in late April to early May at a rate of 15 to 20 lbs pure live seed per acre. *Crambe* needs a firm seed bed and shallow planting depth. Row widths of 6-7 inches are recommended for maximum yield. Nitrogen is added at a rate of 5 lbs N per 100 lbs expected seed yield per acre (about 80-100 lbs N/ac). For soils poor in phosphorous and potassium, 45 lbs/ac $P_2O_5$ and 80 lbs/ac $K_2O$ are recommended. The addition of 20-25 lbs/ac of sulfur is helpful in soils low in sulfur. Weed control, particularly during early vegetative development, is essential as *Crambe* is not a strong competitor with weeds.

*Crambe* reaches harvest maturity about 100 days after planting and is harvested using either swathing and combining, or straight cutting when seed moisture is less than 14%. *Crambe* matures early enough that in some areas, such as those where double cropping of wheat and soybeans is successful, double cropping of *Crambe* might be possible. It is susceptible to *Sclerotinia* and *Alternaria brassicicola* infections, particularly under high moisture conditions. *Crambe* is generally planted in rotation with other small grains. Production and harvest of *Crambe* uses the same equipment as wheat. *Crambe* meal can be feed to ruminants, but is limited to 4.2% of the total weight of the ration by the FDA due to high glucosinolate concentrations in the meal.

*Crambe* has yielded up to 2,500 lbs/ac on small commercial fields and demonstration plots, but typically yields 1,200 to 1,800 lbs/ac in larger commercial fields. *Crambe* seed is somewhat more expensive than wheat seed, otherwise production costs are similar. Transportation costs for *Crambe* are relatively high compared to other small grains. This is partially due to its small size and light weight (25 lbs/bushel), and also because each seed is enclosed in a single hull (about 50% of the seed weight), which remains on the seed after harvest and is transported along with the seed. *Crambe* stubble is sufficient for erosion control, but is brittle and easily destroyed during mechanical operations. Therefore, it is not a likely candidate for crop residue removal.

*Crambe* research focuses on developing higher yielding cultivars, higher oil and erucic acid content, lower seed glucosinolate content, and improved resistance to disease, insects, and seed shatter.

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## Cuphea

The *Cuphea* genus contains about 250 wild species, mostly native to Mexico and to Central and South America. *C. viscosisima* is the only known variety native to the U.S., although four introduced species exist in the wild. *Cuphea* seeds are about 25% oil. Many of the *Cuphea* species contain large percentages of medium chain fatty acids (8-12 carbons) such as capric, lauric, caprylic, and myristic acid (70-90%, depending on variety). Lauric acid is currently used in large quantities in the soap and detergent industry, and is obtained from coconut oil and palm kernel oil. A major constraint to the commercial development of *Cuphea* has been seed shattering; however, discovery of a natural mutation within some *Cuphea* hybrids showing significant reduction in seed shattering has enhanced the opportunity to develop this crop. *Cuphea* plants are covered with sticky hairs that may interfere with harvest activities, but the sticky hairs seem to be a defense mechanism against insects.

*Cuphea* is produced as a summer annual in the U.S. using existing row-crop machinery. It does not tolerate frost, but can still be produced in short season temperate climates as it matures quickly (2-3 weeks to germinate and seed ripening in another 6 weeks). Seed yields in Oregon have ranged from 500 to 1,500 kg/ha (about 450 to 1,350 lbs/ac). Using best management practices, seed yields of up to 1,400 kg/ha (about 1,250 lbs/ac) have been attained in Minnesota. In 2004, 18.6 hectares (46 acres) of *Cuphea* were planted in Minnesota by 6 farmers—some of the crop was lost due to severe weather and herbicide drift from other crops. Yields ranging from 78 to 744 kg/ha (70 to 660 lbs/ac) were achieved. Planting in Minnesota occurs in mid-May. Recent trials indicate that planting *Cuphea* in rotation with corn can help reduce corn rootworm infestations. Expected U.S. production regions for *Cuphea* are the midwest and the northwest. In 2005, 100 acres of *Cuphea* were grown in the U.S.

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## Lesquerella

Lesquerella (*Lesquerella* spp.) is a member of the Brassicaceae and includes herbaceous annual, biennial, and perennial varieties. It is native to North and South America, and 83 of the over 100 known species are indigenous to North America. *Lesquerella* species are of interest because of the high hydroxy fatty acid content of their oil (i.e., lesquerolic acid, densipolic acid, and auricolic acid). Different species can be classified by the predominance of each of these fatty acids. Hydroxy fatty acids have numerous potential industrial uses including lubricants, plastics, protective coatings, surfactants, and cosmetics. The current major source of hydroxy fatty acids is recinoleic acid obtained from castor bean oil. The U.S. annually imports about 41,000 metric tons of castor oil from Brazil and India at a cost of around $100 million.

Commercialization interests have focused on *L. fendleri* because of its growth and yield properties. *L. fendleri* is found throughout the southwestern U.S. (AZ, CO, NM, TX, and UT) and northern Mexico. The potential production area in these states is around 1.4 million acres. *L. fendleri* produces 6 to 25 seeds contained in pods. Seed yields using unimproved varieties in replicated field plots have ranged from 1,000 to 1,350 kg/hectare (900 to 1,200 lbs/ac) and as high as 1,800 kg/ha (1,600 lbs/ac) for improved varieties in test plots. Large scale field trials yield around 900 kg/ha (800 lb/ac). About 25-35% of the *L. fendleri* seed (by weight) is oil and 55-65% of the oil is a hydroxy fatty acid (lesquerolic acid). The seed coat of *L. fendleri* also contains a gum which has industrial uses. The seed meal is 30-35% protein, with an amino acid profile similar to soybeans. The seed contains 3-7% glucosinolates, which must be deactivated for use as a livestock feed.

Although *L. fendleri* is a perennial, commercial cultivation is done as a winter annual. In the southwestern U.S., it is planted by direct seeding in the fall (August-September in TX and NM, and October in AZ) using equipment used to plant alfalfa and clover. No yield differences were found between planting on level fields or raised beds. Raised bed production improves insect and weed control and makes it easier to manage salt buildup, but may decrease harvest efficiency. Seeding rates are about 6 to 8 kg/hectare (5 to 7 lbs/ac). Seedlings emerge 8 to 14 days following planting and remain small until February-March, when temperatures begin to increase. Flowering occurs at this time and the seeds develop and mature between March and late May. *L. fendleri* may be irrigated once every 15-20 days in late February through mid April, and then once every 10 days between late April through mid May (about 25 inches of water total). Seed harvest occurs in mid to late June after the seeds have dried (about 12 percent moisture).

Conventional combines equipped with small sieves to prevent excess seed loss can be used to harvest *Lesquerella*. Nitrogen applications of around 60-120 kg/ha (about 50-100 lbs/ac) improve seed yields. Weed control is important; as is the case with most new crops, additional herbicides labeled for use on *Lesquerella* are needed. Estimated costs of producing *L. fendleri* have ranged from $300 to $550/ac, with differences dependent largely on the extent of irrigation and weed control that is assumed. Improvements in seed yields and management practices are expected to lower these costs.

Research is ongoing to increase seed yields and oil and fatty acid concentrations. Other efforts include breeding for autofertility (to eliminate the need for insect pollination), and development of plants with upright growth habits to improve harvest efficiency. Most varieties of *Lesquerella* have an orange-brown seed coat color, which necessitates pigment removal for use in the cosmetic industry. Development of yellow seed coat varieties is being explored. Research is also underway to develop varieties that flower earlier, which would reduce the need for irrigation.

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## Meadowfoam

Meadowfoam (Limnanthes alba Benth.) is a low growing herbaceous winter annual adapted to poorly drained soils. It is native to northern California, southern Oregon, and Vancouver Island, British Columbia. Meadowfoam seeds contain 20-30% oil; over 90% of the oil contains fatty acids with 20 or 22 carbons and includes three previously unknown long chain fatty acids. The fatty acids are similar to high erucic acid rapeseed, although not as saturated, and display heat and oxidative stability. Meadowfoam oil is currently used in the cosmetics industry and could be used in other industrial applications such as in lubricants, inks, detergents, and plastics. The meal produced from oil extraction can be fed in quantities of up to 25% of the total dietary intake for beef cattle. Use of the meal for other livestock may require heat treatment to reduce glucosinolate levels (a compound toxic to many animals). Meadowfoam meal and extracts are currently being tested as a biopesticide for potatoes.

Meadowfoam has a low tolerance to water stress and is well adapted to cool wet Mediterranean climates, as are found in the Pacific Northwest. In this area, Meadowfoam is typically planted in October (when soil temperatures are below 60°F) at a plant density of 3-4 plants/square foot (seeding rates of 15-40 lbs/ac). Shallow seed drilling is recommended over broadcast seeding. Recommended fertilizer rates are 40-60 lb N/ac, 20 lb $P_2O_5$/ac when soil tests indicate low P levels (10-20 parts per million P), and 20-30 lb $K_2O$/ac when soil tests indicate low K levels (80-100 parts per million K).

Meadowfoam yields in research plots have been as high as 2,000 kg/hectare (1,780 lbs/ac) of seed. However, under commercial field conditions, seed yields of around 750 lbs/acre are more typical, due largely to disease and pollination problems. Meadowfoam is susceptible to the fungus *Botrytis cinerea,* and is insect pollinated. Efforts are underway to develop self-pollinated varieties. Meadowfoam is harvested with the same equipment used in grass seed production. Generally this involves swathing followed by combining, but direct combining harvest methods are being evaluated. Preliminary results indicate less seed loss with direct combining, but this method requires very low moisture content of the stems, leaves, and seeds.

Meadowfoam is currently produced on about 2,000 acres in the Willamette Valley in Oregon, usually in rotation with grass seed production. Attempts to grow Meadowfoam in other parts of the country have been undertaken, most notably in Virginia. In the 1998-

1999 growing season, 120 acres of Meadowfoam were grown in Virginia. Seeds yields of up to 800 lbs/ac (with oil content of 21-25% of the dry weight, 93% long chain fatty acids) were achieved. Recommended management practices include planting 25 lbs seed/ac and adding 30-40 lbs N/ac. Development of cultivars adapted to the area and appropriate management practices to enhance its commercial potential are needed.

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## Epoxy Fatty Acid Oilseed Crops— Vernonia, Stokesia, and Euphorbia

Other potential oilseed crops include *Vernonia*, Stokes aster, and *Euphorbia.* These crops still need a substantial amount of development for commercialization, but are of significant interest because they all are potential sources of naturally occurring epoxy fatty acids. Epoxy fatty acids are currently used in several industrial applications. These include plastics, adhesives, varnishes, paints, and industrial coatings.

These products are currently obtained either from chemically transforming soybean oil or from petroleum.

The *Vernonia* genus includes over 1,000 species, most of which are native to eastern Africa. Initial efforts to develop *Vernonia* focused on *V. anthelmintica,* a variety native to India. These efforts were abandoned due to excessive seed shattering. Recent efforts have focused on *V. galamensis*, an annual plant reaching heights of 0.2 to 2 meters in cultivated fields in the U.S. Seeds of *V. galamensis* are about 30-42% oil, and 73-78% of the oil is vernolic acid. However, as is the case with many equatorial plants, *V. galamensis* flowering is controlled by short day lengths and it cannot be easily grown in the U.S. for seed production. This is because flowering does not occur until the temperature becomes too cold to support growth. Some native day neutral species have been identified and efforts undertaken to create hybrids using *V. galamensis* that are day-length neutral and possess other desirable growth, seed yield, and seed quality characteristics. Breeding efforts are focusing on increasing the quantity of flower heads per plant, increasing seed weight and retention, and removing seed dormancy. Little data is available on cultural management practices, since research to date has been concentrated on only a few research sites in the U.S. Similarly, little information is available regarding seed yields. Production of *V. galamensis* in equatorial African countries has ranged from 1,345 to 2,494 kg/ha (1,200 to 2,200 lbs/ac), but yields of day-neutral varieties in the U.S have been lower (303 to 820 kg/ha; 270 to 730 lbs/ac). It is adaptable to areas with as little as 20 inches of rainfall (apparently rainfall pattern is more important than total rainfall). If appropriate varieties of *V. galamensis* can be developed, they might be suitable for production in the Southwestern U.S.

Stokes aster (*Stokesia laevis*) is native to the southern and southeastern U.S. It displays a substantial amount of genetic diversity, has a high seed oil content (27-44%) and the oil has a high content of epoxy fatty acids (63-79%, principally vernolic acid). Seed retention is good. Stokes aster is a perennial and does not flower during its first year of growth. A possible production approach is to intercrop Stokes aster with a summer annual crop such as soybeans, in order to obtain an economic return on the land during the first year. In limited research efforts, maximum seed yields of 1,000 kg/ha (about 900 lbs/ac) have been obtained and a viable seed production cycle of two years. Genetic and agronomic research is needed to develop this crop.

*Euphorbia (Euphorbia lagascae*) is a drought-tolerant native of Spain whose seed contains about 45-50% oil, of which 60-65% is vernolic acid. Limited research is being conducted in Oregon, mostly with respect to management practices. *Euphorbia* is generally produced as an annual, but does show regrowth after harvest and might be developed as a perennial. Development efforts have been hindered due to seed shattering. No non-seed shattering wild accessions have been found, so efforts have focused on developing mutants that do not shatter.

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## Camelina

*Camelina sativa* (L.) Crantz (also called false flax, linseed dodder, or gold-of-pleasure) is a member of the Brassicaceae and is native to the region extending from the Mediterranean to Central Asia. *Camelina* seeds contain 29-39% oil and consist of about 12% saturated fatty acids, 54% polyunsaturated fatty acids (mostly linoleic and linolenic acids), and 34% monounsaturated fatty acids (mainly oleic and eicosenoic acids). It contains 2-4% erucic acid. The meal contains 45-47% crude protein and 10-11% fiber. It is similar to soybean and flax seed meal (with slightly higher sulfur content than flax) and contains low glucosinolate levels, making it attractive as a livestock feed.

Interest in *Camelina* is being driven primarily for food uses, due to the high linolenic acid (35-40% of the oil) content. Linolenic acid is an OMEGA-3 fatty acid, similar to those found in flax and fish oils. High levels of linolenic acid make *Camelina* undesirable for biodiesel use, but confers a fast drying time for the oil. This makes it suitable for painting and coating applications.

Potential production of *Camelina* is being evaluated in areas where flax is currently produced (i.e., in northern U.S. states such as Minnesota and North/ South Dakota). It may also be possible to grow *Camelina* as a winter crop in areas with mild winters. Due to its short growing season (85-100 days), *Camelina* could possibly be incorporated into double cropping systems. Field trial yields in Minnesota have ranged from 600 to 1,700 kg of seed/ha (535 to 1,515 lb seed/ac) and have averaged 1,100 to 1,200 kg seed/ha (980 to 1,070 lb seed/ac).

*Camelina* can be broadcast planted on frozen ground in late November to early December with emergence in mid-April. Using this method of planting, *Camelina* has been successfully established without the need for site preparation (tillage) or herbicide applications. No-till planting is a viable option. In limited studies, winter-sown *Camelina* produced higher yields when seeded with a fall cover crop than without a cover crop. Use of a cover crop significantly reduces erosion potential. Nitrogen needs appear to be similar to mustard or flax. *Camelina* is somewhat more drought tolerant than flax. Seedlings are cold tolerant and can survive spring freezes, especially when planted at high density (6-14 kg/ha; 5.5-12.5 lb/ac). The early emergence of seedlings also improves the ability of *Camelina* to compete with many annual weeds, potentially reducing the need for herbicides.

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## Jojoba

Jojoba (*Simmondsia chinensis* Link) is a perennial wood shrub native to the Sonoran desert regions of Arizona, California, and Mexico. Jojoba is an oilseed, but unlike most oil seeds that produce oils composed of branched triglycerides, the "oil" of jojoba is composed of long-chain fatty acids (average length of 42 carbons) and fatty alcohols with no side branching (i.e., a liquid wax) that resembles sperm whale oil. Jojoba oil is currently used in the cosmetics industry; other potential industrial uses include high-temperature, high-pressure lubricants, and as an anti-foaming agent.

Jojoba is a dioecious (having separate male and female plants), wind pollinated species. It grows to a height of 10-15 feet and can live for 100-200 years. The fruit is a capsule containing up to three seeds. Seed production generally does not occur until the 4th or 5th year. Jojoba is tolerant of high temperatures, but sensitive to cold and best suited for production in areas that are frost-free. While jojoba is native to arid areas and is drought tolerant, some irrigation may be needed to obtain higher yields and/or to improve stand establishment. It is best suited for production in sandy soils and grows slowly in heavy clay soils, and is tolerant of saline conditions. Jojoba can be planted either by direct seeding or by transplanting seedlings. In the southwestern U.S, direct seeding is generally used because it is less expensive, faster, and requires less hand labor. Jojoba is planted 12-18 inches apart within rows. Spacing between rows depends on whether or not harvesting will be mechanical or by hand. If by hand, rows can be as close as 10 feet apart. For mechanical harvesting, density is about 1,110 plants/hectare (450 plants/ac). Jojoba flowers in winter and is harvested in July. The recommended female-to-male plant ratio is 6 to 1.

Yield trials have not shown any improvement to nitrogen and phosphorus, and application of these nutrients is generally not recommended. In areas where soil tests indicate potassium levels of less than 100 parts per million, addition of 10 to 15 lbs/acre of $K_2O$ is recommended. Seeds on a jojoba plant do not all mature at the same time, so multiple harvests may be required. Harvest is usually by hand, although over-the-row fruit and berry pickers may be used. Jojoba oil that has been dried to 10% moisture and protected from pests can be stored for several years. Jojoba is susceptible to fungal wilts on poorly drained soils.

Seeds in natural stands of jojoba range from a few seeds to 30 lbs of clean, dry seed per plant. Yields vary substantially from stand to stand and, for the same plant, from year to year. Under commercial production conditions, seed yields are about 300 lbs/ac. New clones appear capable of producing up to 800 lbs/ac. The seeds contain 45-65% "oil" by dry weight. Jojoba meal is about 30% protein, and contains simmondsin, a compound that regulates food intake in animals. This generally limits the use of the meal as a livestock feed, but possibly presents other opportunities for its use.

In the United States, current commercial production of jojoba occurs in California and Arizona for use in the cosmetics industry. Recent production data is difficult to find. For 2002, data shows that 88,578 lbs of seed were produced in California on 1,607 acres. Arizona production is shown in table 1.

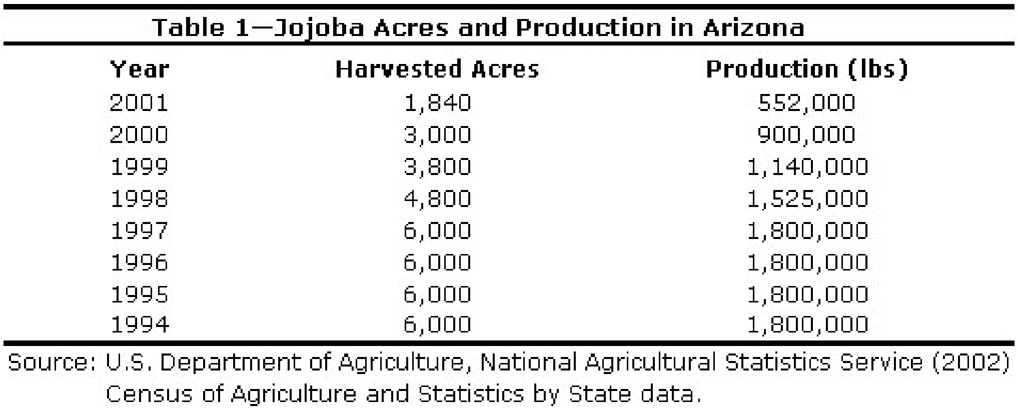

**Table 1—Jojoba Acres and Production in Arizona**

| Year | Harvested Acres | Production (lbs) |
|---|---|---|
| 2001 | 1,840 | 552,000 |
| 2000 | 3,000 | 900,000 |
| 1999 | 3,800 | 1,140,000 |
| 1998 | 4,800 | 1,525,000 |
| 1997 | 6,000 | 1,800,000 |
| 1996 | 6,000 | 1,800,000 |
| 1995 | 6,000 | 1,800,000 |
| 1994 | 6,000 | 1,800,000 |

Source: U.S. Department of Agriculture, National Agricultural Statistics Service (2002) Census of Agriculture and Statistics by State data.

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## Rubbers and Resins

Today, most rubber products are made from petroleum. However, natural rubber is preferred in a number of applications, particularly those that involve high pressures and temperatures (such as high performance tires for race cars and airplanes, among others). The only natural source of rubber is *Hevea braziliensis*, a plant grown in tropical regions of the world. Industrial resins are usually derived from wood sources such as pine trees. Efforts to develop alternative sources of these materials suitable for production in the U.S. include Guayule (rubber) and *Grindelia* (resins).

### Guayule

Guayule (*Parthenium argentatum*) is native to the Chihuahuan Desert of southwest Texas and northern Mexico. At least 16 species have been identified, but *P. argentatum* is the only one being commercialized. During the past century, guayule has intermittently served as a commercial source of rubber (such as during World War II), but sustained commercial production of this crop has not occurred. The bark of guayule is a source of natural rubber (latex) which can be used to make high performance tires and other rubber products. This source could substitute for other natural rubber sources (e.g. *Hevea braziliensis*, a tropical rubber plant) and petroleum derived rubber.

Guayule is a xerophytic perennial shrub which is insect pollinated. It grows best on well drained sand to silty loam soils. In the U.S., production would occur in the Southwest (southern CA, AZ, NM, and TX). Guayule can be grown with minimal irrigation; for maximum rubber yields, some irrigation will be needed. Guayule is generally established by transplanting seedlings, but direct seeding methods are being developed. Seed dormancy has hampered this approach. Guayule plants should be spaced about 0.3 meters apart (about 45,000 plants/ac). Rubber accumulation is seasonal and stimulated by low light and temperature; optimal harvest time is in the spring. Best yields are obtained from plants that are two years old (irrigated) and four years old (dryland). Clipping height and date are important for maximum regrowth. Harvesting the upper portion of the plant (small diameter stems) may provide greater rubber (latex) recovery than harvesting the whole plant, as 76% of the latex is located in small diameter stems (2-10 mm). Harvest is by direct combining. Recommended nitrogen levels are 50-100 lbs N/ac. Temperatures below 4°C will induce semi-dormancy and prolonged freezing temperatures can cause plant death.

Commercial lines of guayule are about 10% rubber by total plant weight. Guayule yields 630 to 830 lbs of rubber/ac/year and a newly developed diploid line has produced up to 1000 lbs/ac/year. Unlike rubber from *Hevea* that is extracted as a bulk polymer, the latex from guayule must be maintained in a stable emulsion during and after harvest. Guayule latex must be protected from oxidation, as well as temperature and pH extremes. Guayule also produces resins (mainly terpenoids), but yields are variable depending on shrub variety, management practices, and processing activities.

Current commercial efforts focus on developing latex products for medical applications such as gloves, condoms, surgical balloons, catheters and tubing, etc. It is estimated that about 10% of the U.S. population is allergic to latex derived from *Hevea.* Guayule latex is hypoallergenic and provides an alternative to rubber medical products made from *Hevea.* The Yulex Corporation has contracted for about 500 acres of guayule production in Arizona as a source for medical latex products, with plans to increase to 3,000 acres in the near future.

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## Grindelia

*Grindelia (Grindelia camporum*) is a herbaceous perennial, native to the western U.S. (particularly the central valley in California). It produces a diterpene resin (grindelic acid) and other resinous compounds on the surface of its flowers, leaves, and stems. In Arizona, experimental lines (under limited irrigated conditions) have yielded up to 5.5 tons/ac, with a crude resin content of up to 11%. The highest crude resin yields are found in the flower heads (about 20%) and leaves (about 14%), with the lowest resin yields in the stems (about 2%). Recently, work in South America has been using *Grindelia chiloensis*, which has a resin content of up to 40%, but lower total biomass yields. Diterpene resins constitute 65 to 75% of the total crude resin produced and are similar to wood rosin and its derivatives. Potential industrial applications include use in adhesives, rubbers, and coatings.

Grindelia is planted at a density of 80,000 plants/hectare (about 32,500 plants/ac). In Arizona field trials (under irrigated conditions), stands were planted in October, harvested in late June and again in late September, and yielded a total of 12.5 dry Mg/hectare (5.6 dry tons/ac) with an average crude resin yield of 9.4%. Trials in Oregon produced biomass yields of 0.75 to 15.5 dry tons/ac (depending on soil type and production practices). *Grindelia* would most like be produced in the western U.S. in warm, dry areas. Research is focusing on increasing total biomass yields, resin content, and agronomic practices.

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## Non-Wood Fiber Crops

Most new fiber crops are being developed with the intent to provide a new source of fiber for traditional fiber uses (e.g. paper, packing materials, fiberboard, bedding, etc.). However, many of these crops could also potentially be used to produce new composite fiber materials, as well as a cellulose feedstock for bioenergy and bioproduct production. A number of crops have been identified as possible candidates, but most development efforts have focused on Kenaf and Hesperaloe.

### Kenaf

Kenaf (Hibiscus cannabinus L.) is a warm season annual that is closely related to cotton and okra and is native to east-central Africa. Kenaf contains moderately long bast-like fibers in its outer bark and balsa wood-like short fibers in its inner core. The outer stem (bark) is 30-35% of the stem weight and the fiber content of the bark is 50-55%. The core comprises the remaining 60-65% of the stem weight. The short fibers make up about 45-50% of the core. The bast fiber is used to produce products such as burlap, carpet padding, and pulp. The short-fibered core is used for bedding, packing materials, and absorbent mats, etc. Although developed as a fiber crop, kenaf could potentially be used as a livestock feed. Crude protein content in kenaf leaves, stalks, and total plant ranged from 14-34%, 2-12%, and 6-23% respectively. Because of its relatively high yields, kenaf could also be a source of cellulose material for bioenergy and bioproducts.

Kenaf generally requires a long growing season (as occurs in the southern U.S.), where it can reach heights of 12-18 feet and produce 5-10 dry tons of fiber/ac. It is planted by direct seeding (using row crop planters or grain drills) after the danger of frost has passed and soil temperatures exceed 55° F. A firm seedbed is necessary and ridge-till might be an effective planting option in more northern areas. Kenaf is densely planted (75,000 to 120,000 plants/ac; 6 to 14 lbs seed/ac). Fertilizer application rates are generally around 100 to 150 lbs N/ac, and 60 lbs $P_2O_5$/ac and 90 lbs $K_2O$/ac when soil tests indicate low P and K levels. Kenaf is suspectible to root-knot nematodes. Due to the photosensitive nature of most varieties planted in the U.S., seed production is limited to frost-free areas in southern FL, TX, AZ, and CA. Kenaf reaches maturity in about 150 days and is harvested once, in late fall or winter. Various harvesting methods can be used, including the use of standard forage harvesters and hay balers or modified sugar cane harvesters. Estimated production costs vary by location. A recent Tennessee study estimates the cost at $287/ac ($2004), assuming the above management practices, baling, and 7.2 dry tons/ac yields. For kenaf to be more profitable than other crops (corn, soybeans, wheat, and cotton) in the three TN counties examined, a price of $49/dt was needed. Approximately 8,000 acres are currently planted with kenaf, mostly in TX, MS, GA, and LA.

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## Hesperaloe

*Hesperaloe* is a desert plant native to northern Mexico. Two species, *H. funifera* and *H. nocturna*, are being examined as possible new fiber crops. The fiber cells of *Hesperaoloe* are unusually long and thin (3-4 mm long and 14-17 microns wide). This high length-to-width ratio is found only in a few other specialty fibers, such as abaca and sisal. While *Hesperaloe* can be used to produce specialty papers, its largest market opportunity may be as a blend material to use with other fibers, which increases strength, softness, and other performance characteristics. *Hesperaloe* could also be used as a cellulose feedstock for bioenergy and bioproducts.

*H. funifera* and *H. nocturna* display compact growth habits and may be grown at a high stand density. They are water efficient, but commercial production will probably require irrigation in the Southwest. Seeds are scarce and slow to germinate, requiring stand establishment using transplanted seedlings. Initial growth is slow and *Hesperaloe* is not competitive with weeds in the first few years, requiring weed control.

The projected crop cycle for Hesperaloe consists of stand establishment, with transplants in year one, first harvest in year five, second harvest in year eight, and third harvest in years ten or eleven. Total combined fresh weight yields of the three harvests are projected to be around 250 metric tons/ac (275 tons/ac), based on a planting density of 8,700 plants/ac. The dry fibrous material represents about 30% of the leaf fresh weight. Efforts are underway to develop mechanical means to efficiently harvest *Hesperaloe* leaves.

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## Herbaceous (Grass) Crops

In the U.S., much of the effort to develop new bioenergy and bioproduct crops has focused on herbaceous grasses and short rotation woody crops that can be used as cellulose sources. Almost any grass can be used as a cellulose feedstock, but current efforts center on developing grasses that can be produced with high yields on large acreages, using commercial agricultural production systems. Many of the species of interest are currently grown as forage crops for livestock. However, the varieties and management practices best suited for forage production are not necessarily those most appropriate for bioenergy and bioproduct uses. Therefore, new varieties and production systems need to be developed. The herbaceous grass receiving the greatest attention in the U.S. is switchgrass (*Panicum virgatum*). The major focus of the Europeans has been on *Miscanthus*, and this crop is creating interest in the U.S. as well. A number of other grass crops could also be used for bioenergy and bioproducts, but research is limited. Among those most commonly mentioned as potential candidates are *Arundo donax* and reed canary grass.

## Switchgrass

Switchgrass (*Panicum virgatum*) is a warm season perennial whose native range includes all of the U.S. east of the Rocky Mountains, extending into Canada and Mexico. It is a major species of the prairies that covered much of the American heartland prior to the introduction of agriculture. Switchgrass is a C4 species (i.e., the first product of photosynthesis is a four carbon compound), consists of numerous upland and lowland varieties, and displays substantial genetic diversity. Switchgrass has been produced as a forage crop and used for conservation purposes for many years. Its development as a potential energy crop began in 1991 as part of the U.S. Department of Energy's Biomass Feedstock Development Program at Oak Ridge National Laboratory. Field trials were  established at 18 sites (13 states including VA, WV, TN, KY, NC, GA, AL, TX, AR, LA, ND, SD, and IA). Nine cultivars were evaluated to identify best regional varieties, establish appropriate management practices, and conduct genetic research to improve yield and performance characteristics. The Alamo variety was determined to be the best cultivar tested for production in the South, Alamo and Kanlow best for mid-latitude production, and Cave-in-Rock, Trailblazer, and Sunburst varieties best suited for northern latitudes.

Under research conditions (5-10 years data; one cut production system, multiple sites and states), yields of genetically unimproved Alamo averaged 12 to 19 Mg/ha/year (5.35 to 8.45 dry ton/ac/year) and genetically unimproved Kanlow averaged 11.6 to 15.5 Mg/ha/yr (5.2 to 6.9 dry tons/ac/year) respectively. The best one year yield attained under a two cut system was for Alamo in Alabama (34.6 Mg/ha; 15.4 dry tons/ac). Both Alamo and Kanlow varieties produce high yields in the South (except for arid conditions in TX) under a one and two cut system, maintaining high yields for a number of years. However, two cut systems are more intense and require greater energy and nutrient inputs than single cut systems. The oldest continuous research plot for Alamo was established at Auburn University in 1988 and has averaged 23 Mg/ha (about 10 dry tons/ac) over a 13 year time period. First generation synthetic cultivars (hybrids) are yielding up to 30% higher yields than their unimproved counterparts, but are still being evaluated and are not yet commercially available.

Switchgrass is a perennial and needs planting only once during a multi-year period. Generally, a ten year production rotation is assumed before replanting, but periods of different lengths are possible if circumstances warrant. Switchgrass has a deep root system—the below ground biomass is as great as the above ground biomass. This large and deep root system, combined with fine root turnover, makes switchgrass an excellent crop for erosion control. It may also be used as an organic matter additive for depleted soils.

Switchgrass is produced using standard agricultural equipment. It requires a firm seedbed and a shallow planting depth, making it appropriate for no-till planting. Seed density must be sufficient to provide a good stand (2 plants/sq ft; 7-8 pounds pure live seed/ac). Weed control is required in the establishment (first) year and usually consists of one pre-emergent herbicide application and 1-2 post-emergent applications. Herbicides are generally not required after the establishment year. At the current time, few herbicides are labeled for use on switchgrass; more are needed.

Switchgrass is nutrient and water efficient and requires no fertilizers in the establishment year. Nitrogen is applied annually in subsequent years at recommended rates of 50 lbs N/ac for most regions (up to twice this level under some circumstances, such as in the South Plains where little nitrogen is available from soil mineralization). Phosphorus and potassium are added only if soil tests indicate low levels. Recommended rates are around 15-20 lb P/ac and 25 lb K/ac. Switchgrass tolerates acid and alkaline soils within a range of pH 4-8 and will not require lime under typical production conditions. These recommended rates are appropriate for production systems consisting of one harvest per year following senescence, which allows nutrients to be translocated to the roots for use in the following growing period. Production systems involving more than one harvest per year, including harvest during the active growing period, require higher levels of nutrients. Switchgrass resists lodging, and can be harvested anytime after senescence and before shoot emergence the next spring, if the ground is sufficiently dry to permit harvest.

Switchgrass typically takes three years to reach its full mature yield, although harvest can still be conducted in the first two years. Yields in the first (establishment) year are typically 20-35% of mature yields and in the second year are typically 60-75% percent of mature yields. Switchgrass can be produced throughout the U.S., but research and development efforts have mostly been limited to areas east of the Rocky Mountains. Expected yields and estimated production costs vary substantially by region.

Switchgrass is not currently produced as a bioenergy crop in the U.S. and large scale production for this use will require switchgrass to compete with existing uses for agricultural land. A recent U.S. DOE study estimated that by mid-century, 163 million dry tons of switchgrass could potentially be available on non-Conservation Reserve cropland acres (based on an assumed removal rate of 4.2 dry tons/ac on 35 million acres of cropland drawn primarily from pasture, hay, and fallow acres). Under a high crop yield scenario, the study estimates that 368 million dry tons could be available (assuming removable yields of 6.7 dry tons/ac and 55 million acres of production with acres coming mostly from pasture, hay, fallow, wheat and soybean acres). No economic analysis was conducted.

A recent economic study that examined the commercial potential to produce switchgrass throughout the U.S. estimated that 293 million dry tons of switchgrass could potentially be supplied at a price of $50/dry ton or less by the year 2025 (table 1). The study used a dynamic model of the U.S. agricultural sector (POLYSYS) that shifts cropland acres from current uses to switchgrass production, based on relative profits. The analysis assumed expected 2005 regional harvest yields (cropland acres, rainfed conditions) ranging from about 2-6.5 dry tons/ac (figure 1, page 34). Yield increases ranging from 20-60% (depending on region) were assumed between 2005 and 2025. Estimated current regional production costs ($2002/dry ton) used in the analysis are shown in figure 2 (page 34).

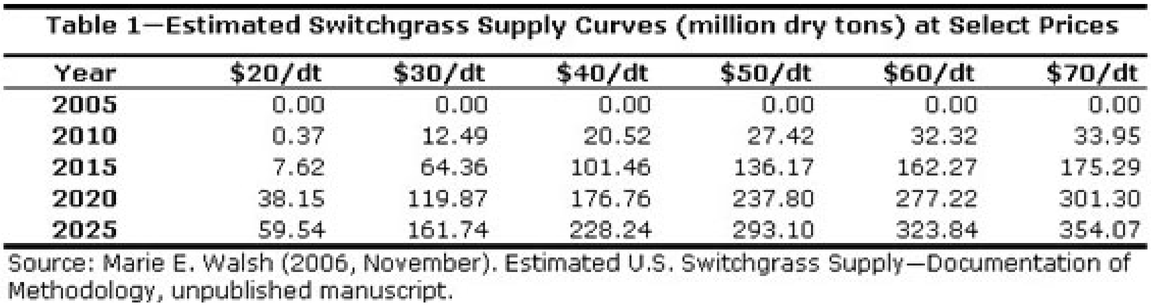
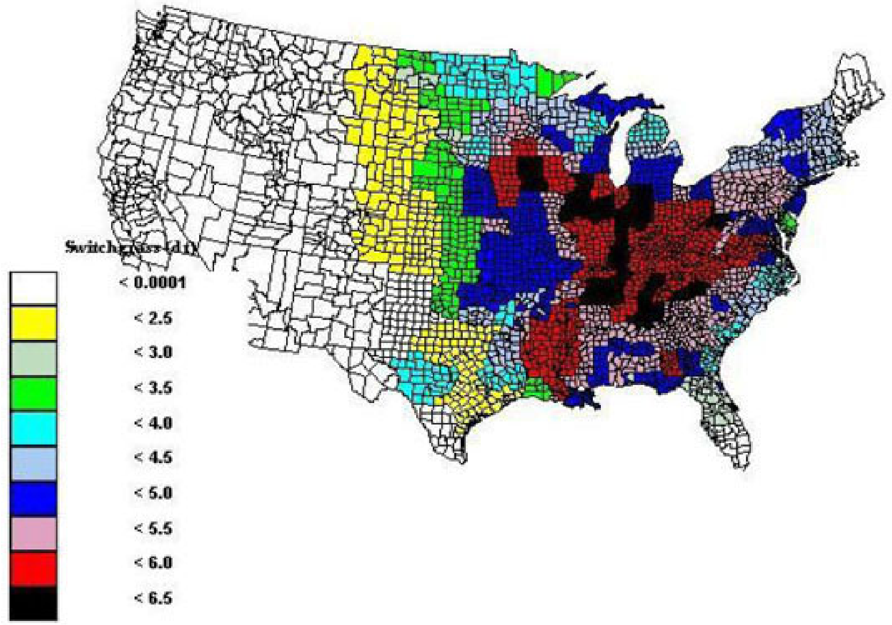


**Table 1—Estimated Switchgrass Supply Curves (million dry tons) at Select Prices**

| Year | $20/dt | $30/dt | $40/dt | $50/dt | $60/dt | $70/dt |
|---|---|---|---|---|---|---|
| **2005** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **2010** | 0.37 | 12.49 | 20.52 | 27.42 | 32.32 | 33.95 |
| **2015** | 7.62 | 64.36 | 101.46 | 136.17 | 162.27 | 175.29 |
| **2020** | 38.15 | 119.87 | 176.76 | 237.80 | 277.22 | 301.30 |
| **2025** | 59.54 | 161.74 | 228.24 | 293.10 | 323.84 | 354.07 |

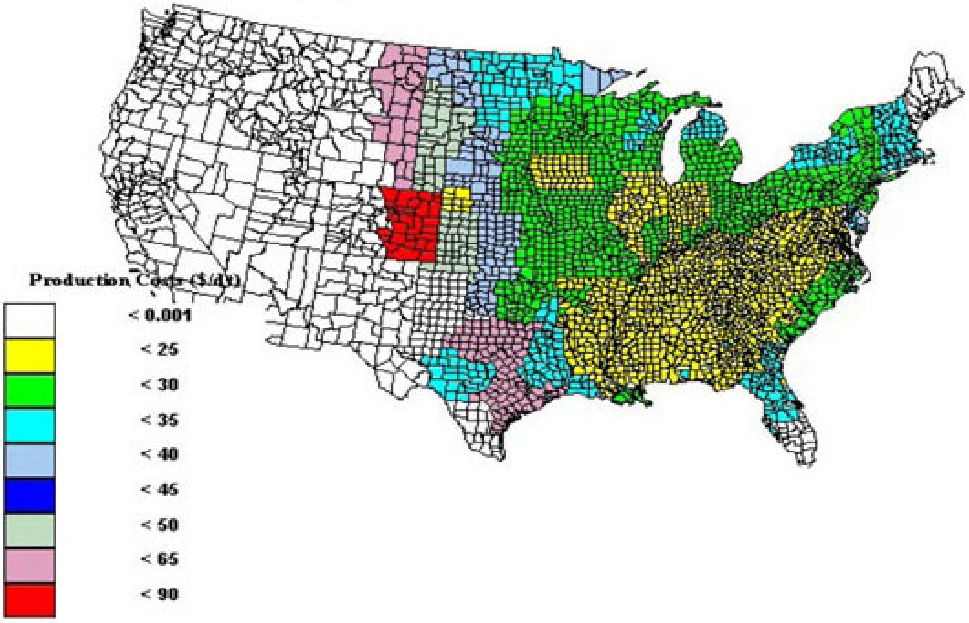
Source: Marie E. Walsh (2006, November). Estimated U.S. Switchgrass Supply—Documentation of Methodology, unpublished manuscript.

Figure 1—Expected Switchgrass Harvest Yields by Region (dry ton/acre) Year 2005



Source: Marie E. Walsh. (2006, November). Estimated U.S. Switchgrass Supply—Documentation of Methodology, unpublished manuscript.

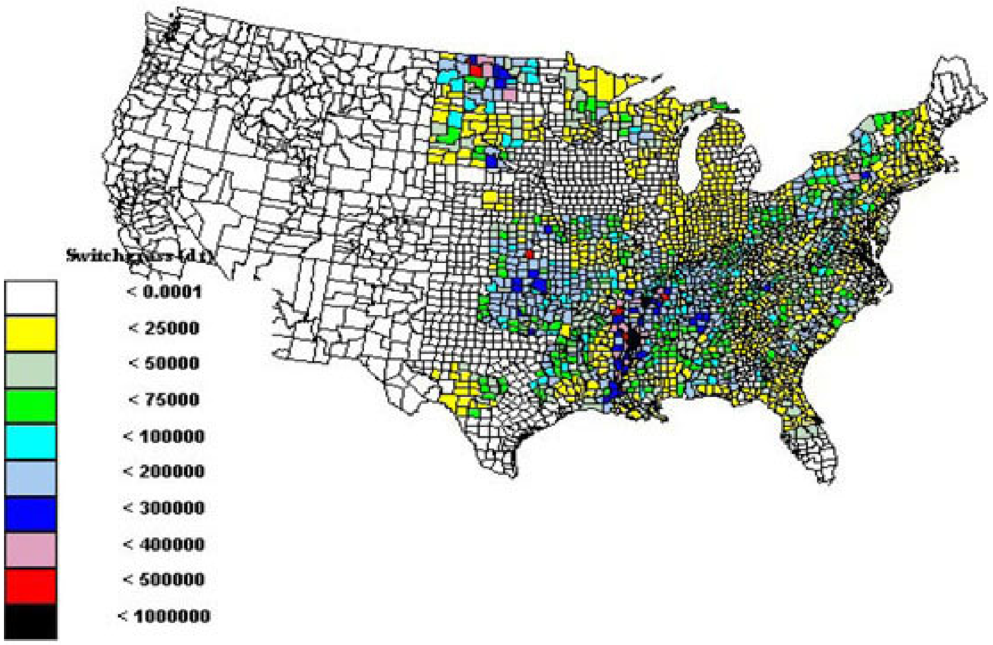
Figure 2—Estimated Switchgrass Production Costs by Region ($2002/dry ton)—Year 2005.



Source: Marie E. Walsh. (2006, November). Estimated U.S. Switchgrass Supply–Documentation of Methodology, unpublished manuscript.

Estimated costs range from less than $25/dry ton to nearly $90/dry ton, depending on region. Production costs are estimated as net present costs over the entire rotation, using American Agricultural Economics Association recommended methodology. This includes the costs of seed, fertilizer, herbicide, operating interest, producer's own labor, and the costs associated with owning and operating equipment (fuel, oil, and lubrication; depreciation and interest; repairs; and insurance, taxes, and housing). Harvest assumes mowing, raking, baling (large round bales), moving the bales to the edge of field, and stacking. The estimated costs include regional variation in input prices. Establishment and fertilizer costs remain unchanged throughout the period of the analysis, but it assumed that new harvesting methods will be developed, which will reduce harvests costs over time (a maximum reduction of 25% by 2025). Figure 3 shows the regions where switchgrass production is most competitive with existing land uses for the year 2015, assuming a crop price of $40/dry ton. Switchgrass is most competitive with existing land uses in the southeastern and northeastern U.S. and in a ring surrounding the Corn Belt.

Figure 3—Regions Where Switchgrass is Economically Competitive with Existing Uses of Agricultural Land (Year 2015, $40/dry ton)



Source: Marie E. Walsh. (2006, November). Estimated U.S. Switchgrass Supply–Documentation of Methodology, unpublished manuscript.

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## Miscanthus

*Miscanthus* is a perennial plant native to tropical and subtropical Asia and is related to sugar cane. It is a C4 species (i.e., the first product of photosynthesis is a four carbon compound) and nutrient efficient. Very limited research has been conducted on this species in the United States. Recent studies in Illinois (from small research plots at three sites) report yields of 14.4, 24.6, and 19.6 tons/ac in the third year of production. Research is being expanded to include more sites in Illinois. *Miscanthus* has been the focus of extensive research in Europe. It is not clear how much of the European experience can be directly extrapolated to conditions in the U.S., but as *Miscanthus* has recently been receiving increased interest in the U.S., the European experience is summarized.

Efforts to evaluate *Miscanthus* as a potential bioenergy crop began in 1989 and since then have included field trials in Denmark, Germany, Ireland, United Kingdom, Greece, Italy, Spain, the Netherlands, Austria, and Switzerland. Nearly all of the research has involved *Miscanthus x giganteus* (a cross between *M. sacchariflorus* and *M. sinensis)*, a sterile hybrid that prevents invasive characteristics that have been experienced with some varieties of *Miscanthus*. However, development of a large scale industry based on such a limited genetic foundation can be problematic; recently, research to develop and evaluate additional hybrids has begun.

*Miscanthus x giganteus* is somewhat cold sensitive (particularly in the first year of production) and in areas with cold winters, problems with winter kill have occurred. Initial planting efforts involved growing plantlets in greenhouses and transplanting to the field—an expensive establishment method. Recent research has focused on developing establishment procedures that involve planting pieces of rhizomes using a modified potato planter or similar machinery. Not only is this approach less costly, but appears to enhance the winter survival of first year plants. Planting density is 1 plant/meter$^2$. Weed control is required in the establishment year (and sometimes the second year) and usually consists of one pre-emergent herbicide application and one to two post-emergent applications. *Miscanthus x giganteus* is nutrient efficient and requires no fertilizers in the establishment year. Nitrogen is applied annually in subsequent years at recommended replacement rates of 2-5 kg N, 0.3-1.1 kg P, and 4-8 kg K per ton of dry matter harvested. Fertilizer is applied in the spring prior to new growth. *Miscanthus x giganteus* can successfully be produced without irrigation in north-central Europe; it may need to be irrigated in southern Europe in order to achieve satisfactory yields.

Under favorable conditions, *Miscanthus x giganteus* can be high yielding, but shows a substantial range in potential yields. Table **1** summarizes yields of mature stands (at least three years old) in several European trials. The low yields occur on soils termed "poor" with higher yields on "good" soils. The high yields attained in the southern European countries involve irrigated production.

*Miscanthus x giganteus* harvest typically occurs in February and March (especially in Northern Europe). Delayed harvest allows *Miscanthus* to field dry to less than 20% moisture, relocates nutrients to the rhizomes for use in the subsequent growing period, and improves the chemical composition of the plant for industrial (most notably combustion) uses. However, during this time, the leaves and tops fall off, reducing the available biomass. This biomass reduction, combined with equipment limitations, results in harvestable yields of 50-70% of the yields attained at the end of the growing season. Additionally, yields attained in small research trials are higher than are attained in large scale commercial production situations using typical production practices. Expected commercial harvest yields are estimated to be 7-12 dry MT/hectare (3-5.3 dry tons/ac) (higher yields on humid soils and lower yields on dry soils). *Miscanthus x giganteus* takes 2-5 years to reach full maturity. Expected production cycles are 15-25 years before replanting is needed.

The historical estimated costs of producing *Miscanthus x giganteus* have been high, mostly due to high establishment costs associated with transplanting plantlets. Mechanical planting of rhizomes substantially reduces costs. Harvest generally includes cutting using a modified forage harvester, followed by raking and baling. Research is underway to improve the efficiency while reducing harvest costs and biomass losses.

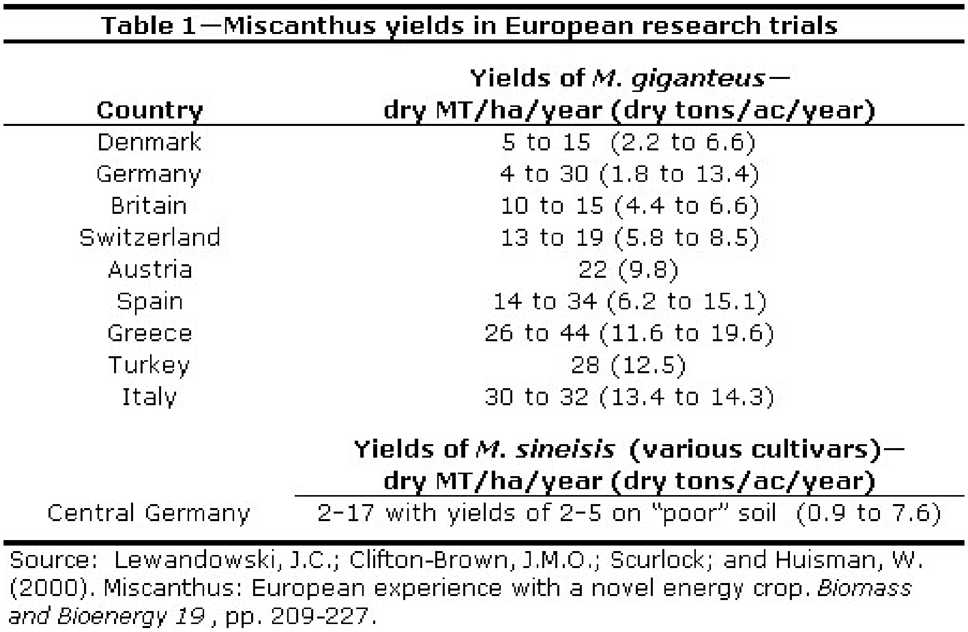

**Table 1—Miscanthus yields in European research trials**

| Country | Yields of *M. giganteus*—dry MT/ha/year (dry tons/ac/year) |
|---|---|
| Denmark | 5 to 15 (2.2 to 6.6) |
| Germany | 4 to 30 (1.8 to 13.4) |
| Britain | 10 to 15 (4.4 to 6.6) |
| Switzerland | 13 to 19 (5.8 to 8.5) |
| Austria | 22 (9.8) |
| Spain | 14 to 34 (6.2 to 15.1) |
| Greece | 26 to 44 (11.6 to 19.6) |
| Turkey | 28 (12.5) |
| Italy | 30 to 32 (13.4 to 14.3) |
| | **Yields of *M. sineisis* (various cultivars)—dry MT/ha/year (dry tons/ac/year)** |
| Central Germany | 2-17 with yields of 2-5 on "poor" soil (0.9 to 7.6) |

Source: Lewandowski, J.C.; Clifton-Brown, J.M.O.; Scurlock; and Huisman, W. (2000). Miscanthus: European experience with a novel energy crop. *Biomass and Bioenergy 19*, pp. 209-227.

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## Miscellaneous Other Grasses

### *Fibercane*

*Arundo donax* (also called giant reed or fibercane) is a member of the reed family and is a warm season, $C_3$ perennial grass. It is native to southern Europe. It is commercially produced as a source of reeds in woodwind instruments and has been examined for paper and pulp applications. It can grow up to 20 feet tall in the southern U.S. and has hollow stems. It produces large seedheads, but the seeds are not viable and it needs to be propogated from vegetative material such as shoots or rhizomes. Establishment and harvesting can be accomplished with the same equipment as is used for sugarcane production. Annual yields in Alabama on test plots from 1999 to 2004 were 1.4, 8.8, 12.9, 14.3, 14.6, and 19.7 dry tons/ac. *Arundo donax* is classified as a noxious pest or invasive species in a number of states. This designation arises from problems encountered when rhizomes have escaped production regions and become established on riverbanks and wetland areas where it out-competes native plants.

### *Reed Canary Grass*

Reed canary grass (*Phalaris arundinacea*) is a cool season $C_3$ grass native to temperate regions of Europe, Asia, and North America and adapted to much of the northern U.S. Reed canary grass grows well in cool temperate climates and displays good winter hardiness. It is established by seeding at shallow depths in firm seed beds and harvested using standard haying equipment. In the U.S., reed canary grass is used as a livestock forage crop; thus, research has generally involved improving yields and selecting for nutritional quality. It has been evaluated as a bioenergy crop in Sweden for more than ten years, where yields of 9 dry MT/ha were achieved with fall harvest and 7.5 dry MT/ha with spring harvest (eight year average). Recommended fertilizer rates are 40 kg N, 15 kg P, and 50 kg K/ha in the first year and 100, 15, and 80 kg/ha of N, P, and K in subsequent years.

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### *Mixed Grass Systems*

Nearly all of the research to develop herbaceous grasses as bioenergy and bioproduct feedstocks involves monocultural management systems. But, at least from a feedstock point of view, mixed grass systems may offer yield and environmental advantages. In Minnesota, data from the Cedar Creek Experiment Station indicate that diverse prairie grasslands consisting of 2, 4, 8, and 16 species produced 84, 100, 157, and 238% more biomass than plots with single species (average for years 2003-2005 for plots planted in 1994). Additionally, yields varied less from year to year in stands with many species, relative to single species stands. However, research evaluating the potential to develop mixed grass stands for bioenergy and bioproduct use is limited. Researchers in Minnesota and North and South Dakota are evaluating switchgrass as a monocultural system and in a mixed grass system with big bluestem and indiangrass. Limited research by the USDA is occurring in the southeast.

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## Short Rotation Woody Crops

### Hybrid Poplar

Hybrid poplars (*Populus spp.*) are fast growing, short rotation trees being developed for fiber and bioenergy uses. Hybrid poplars are crosses between native cottonwoods (the most common being *Populus deltoids* crossed with *Populus trichocarpa*) and are close relatives to aspens. Hybrid poplars can be produced throughout the U.S. where sufficient water is available. The U.S. Department of Agriculture Forest

Service began work to develop hybrid poplars in the early 1970s. This became the foundation for the U.S. Department of Energy's Biomass Feedstock Development Program efforts to develop the hybrid poplar as a bioenergy crop, beginning in 1979.

Hybrid poplars have short production cycles: 6-8 years in the Pacific Northwest, 8-10 years in the Midwest, and 10-12 years in the Southeast. They are typically planted at spacings ranging from 8 x 8 feet to 12 x 12 feet (wider in the Pacific Northwest, narrower in the Southeast; 300 to 700 trees/ac). Yields range from 4 to 10 dry tons of wood/ac/year. Native forests typically grow at a rate of less than one dry ton/ac/year, while managed pine plantations generally produce about 2.5 dry ton/ac/year. The higher yields have been achieved in the Pacific Northwest and Midwest. Yields in the southeast tend to be at the lower end. Hybrid poplars can resprout from their roots after harvest (coppice). However, replanting is the management approach generally recommended,to take advantage of improved varieties while minimizing potential insect and disease problems.

Hybrid poplars prefer well-drained slightly alkaline soils (pH 5-7.5). The soil is generally plowed to a 10 inch depth and cuttings (about 10 inches long) are planted either manually or mechanically, with just the top bud showing. Weed control in the first year is essential and likely some weed control in the 2nd and possibly 3rd years may be needed (depending on spacing and tree growth - once canopy closure occurs, weed control is not needed). Fertilizer needs are low. Nitrogen is generally applied only if the nitrogen levels in the leaves fall below 3% on a dry weight basis. Typically, this means that 1-2 applications of nitrogen at levels of up to 50 lbs N/ac are required during the entire production cycle. Hybrid poplars are susceptible to leaf rust caused by *Melampsora spp.* and stem canker caused by *Septoria musiva*. Hybrid poplars are harvested with standard forest harvesting equipment (i.e. feller bunchers, skidders, forwarders, chippers, etc.).

A recent economic analysis, using a dynamic model of the U.S. agricultural sector (POLYSYS), estimated that when competing for cropland acres with existing crops (i.e. corn, soybeans, etc.) as well as other potential bioenergy crops (i.e. switchgrass and willow), hybrid poplar was less competitive as a dedicated bioenergy crop than switchgrass. This result was due largely due to higher production costs and lower yields for hybrid poplar relative to switchgrass. This means that even though poplars have a slightly higher energy content than switchgrass, at any given energy price ($/btu) switchgrass was more profitable than poplars under most conditions examined. Estimates of the cost of producing hybrid poplar vary substantially, but for the purpose of this analysis costs ranged from $917 to $1051/ac ($1998) and expected harvested yields ranged from 34.5 to 46.3 total dry tons/ac, depending on region.

Analysis by the U.S. Department of Agriculture Forest Service (using POLYSYS and the North American Pulp and Paper Model) examined the potential of hybrid poplar as a future fiber crop (years 2000 to 2036), rather than as a bioenergy crop, under a number of technical, economic, and forest industry assumptions. Depending on the scenario, the analysis estimated that a total of 15 to 800 million cubic meters of hybrid poplar (6.4 to 343 million dry tons, based on an assumed density of 24 dry lbs/cubic foot) could be harvested for pulpwood over the 36 year time period, mostly in the period following 2020 (an annual harvest of 50-60 million cubic meters [21.4-25.7 million tons] under the highest scenario). Production occurred in the Southeast under the low production scenarios, spread to the Midwest, and then to the Pacific Northwest under the higher production scenarios. The production levels correspond to 0.1 to 1.8 million hectares (0.247 to 4.45 million acres) of hybrid poplar production. The study did not include the potential to use Conservation Reserve Program acres. The level of production is this study bounds the results obtained from a previous analysis using the NAPAP model and FASOM (Forest and Agricultural Sector Optimization Model), which estimated 0.6 to 1.0 million hectares (1.48 to 2.47 million acres) of land could be converted to poplar production. More recent analysis by the Forest Service estimates approximately 0.1 billion cubic feet (1.2 million dry tons) of hybrid poplar could potentially be produced annually for fiber by 2050.

An analysis of poplar production for fiber uses on agricultural lands in the Southeast (assumed transport distance of 50 km) estimated delivered breakeven costs to a pulp mill of $75.58 to $89.28/dry ton, depending on delivered form (i.e. roundwood or chips) and the year of harvest (years 5 through 10) for yield levels that are currently achievable (20 green tons/hectare/year), and $57.42 to $68.92/dry ton for the same scenario but with yields of 30 green tons/hectare/year. The analysis assumes irrigation and includes the cost of installing irrigation lines. Land costs are also explicitly included. Other costs include site preparation, cutting costs, weed and insect control, fertilizer, irrigation costs, labor, a custom harvest charge, and transport costs.

A recent Department of Energy study estimates that by mid-century, 9.2 million dry tons of short rotation woody crops could be available for bioenergy use. The estimate is based on the assumption of short rotation woody crop production on 5.1 million acres of non-Conservation Reserve Program acres, an average yield of 8 dry tons/ac of fiber, and 25% of the production being available for energy with the remainder used for fiber. No economic analysis was conducted.

At the present time, over 90,000 acres of hybrid poplar have been planted for commercial production. Most crops in the Pacific Northwest are grown for fiber rather than energy. However, 5,000 acres in Minnesota are part of two large-scale demonstration projects, and there are smaller acreage models in the midwest and southeastern U.S.

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## Willow

Development of willow (*Salix spp*.) as a bioenergy crop began in the mid 1980s. Most of the research focuses on developing willow for production in the northeastern and Mid-Atlantic U.S.

The sites for willow production are generally prepared in the summer or fall and include mowing (on sites currently in grass) and an application of herbicide, followed by plowing and disking before winter. A final cultivation is conducted the next spring, followed by an application of a pre-emergent herbicide immediately prior to planting. Fall site preparation increases the potential for soil erosion; alternative site preparation methods are being explored, including no-till planting, use of cover crops, and strip tillage methods. Good results have been obtained with the use of a rye cover crop. Willows stands are densely planted (15,300 plants/hectare; 6,180 plants/ac) in a double row system (5 feet between double rows, 2.5 feet between the rows, and 2 feet between plants within rows). Mixtures of different varieties, planted within a stand either as blocks or as random mixtures within rows, is recommended. Planting can use either 10 inch long cuttings using a 2 row planter (Froebbesta) or 4-7 foot long whips using a four row (Step) planter. Immediately following planting, a pre-emergent herbicide is applied. Specially designed cultivators can be used to mechanically control weeds until canopy closure, when weed control is no longer needed. At the end of the first growing season (after leaf fall and before spring buds appear, typically November to early March), the trees are cut back using a sickle bar mower. Coppicing promotes multiple sprouts from a single root system. Nitrogen fertilizer is applied during the second season, generally at a rate of about 100 lbs

N/ac. Potassium and phosphorus are applied as needed. The first harvest of willows occurs in the 4th year, and every 3rd to 5th year thereafter. It is anticipated that willow can be harvested 6 to 7 times before replanting is needed. Harvesting is done by a modified Claas Jaguar corn harvester or a Bender harvester attached to a tractor, usually during the winter months. Fertilization occurs in the spring following harvest (100 lbs N/ac, and potassium and phosphorous if needed).

Between 1998 and 2000, over 500 acres of willow were established in New York; smaller trials have been established in nine states and southern Quebec. The New York trials involve 14 landowners with field sizes ranging from 5 to 100 acres, with smaller fields being planted adjacent to one another so that no collection site is less than 20 acres. First rotation yields of the best clones ranged from 3.7 to 5.1 dry tons/ac/year (8.4 to 11.6 dry metric tons/hectare/year). Second rotation yields of the best clones have increased by 18 to 62%, depending on site. Yields of 12 dry tons/ac/year have been achieved on fertilized, irrigated stands grown for three years. First rotation yields of the most consistent clones averaged 7.4 dry Mg/ha/yr (3.3 dt/ac/yr) under commercial scale conditions.

The equipment used to plant and harvest willow was developed in Sweden and is currently not routinely available in the United States. The trend in planting is to use the Step planter because it is faster, uses less labor, and alleviates the need to cut the whips into 10 inch cuttings, thus reducing costs. However, the Froebbesta planter is a smaller machine that is easier to operate with a small tractor and may be more appropriate for planting small parcels of land. Good results in Europe have been obtained with a Bender harvester that cuts and chips willow to a consistent and acceptable size. However, testing in the U.S. has been unsuccessful - primarily due to the higher yields, larger diameters, and higher wood density of the willows in the U.S. relative to Europe. Alternative harvesting equipment (such as forage harvesters with specially designed willow cutting heads) are being tested.

Currently, willow planting stock is produced at two facilities in New York and generally requires 2 to 3 years to produce cuttings and whips.

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## Miscellaneous Other Short Rotation Trees

Sycamore (*Platanus occidentalis)* is a fast growing, long-lived tree native to most of the U.S. east of the Great Plains. It naturally grows in bottomlands and tolerates wet soils. Sweetgum (*Liquidambar styraciflua*) is a bottomland hardwood native to most of the southeastern U.S. and is an important commercial hardwood species. An estimated 800 $km^2$ of hardwood plantations have been established in the southern U.S., of which about 30% are owned by the forest industry. Sycamore grows more rapidly than sweetgum in the early years of a rotation and can produce more than twice the biomass of sweetgum in short rotations (i.e. about 5 years). However, sycamore growth slows after a number of years, while sweetgum growth accelerates later in the rotation, so that in longer rotations (10-15 years) overall production may be similar.

Production of sycamore and sweetgum for bioenergy may differ from production for fiber, in that the trees are planted at close spacing (using cuttings), harvested in rotations ranging from 4-10 years, and in some cases, allowed to resprout (coppice) from the harvested stumps rather than replanted. Yields ranging from 5-13 dry tons/ac/year have been reported.

Silver maple (*Acer saccharinum*) is a medium sized tree native to the eastern U.S. and is used as a source of maple lumber. It is often planted as an ornamental but has been suggested as a potential bioenergy crop.

*Eucalyptus globulus Labill* is native to Tasmania and is the most widely planted Eucalyptus variety in the world. It was introduced to California in 1856 and Hawaii in 1865. Around 40,000 and 12,000 acres of *Eucalyptus globulus L*. are planted in California and Hawaii respectively. *E. globulus* grows best in mild, temperate climates or high, cool elevations in tropical areas. It coppices (regrows) readily from stumps of all sizes and ages. In the U.S. it is mainly produced for pulp, however, efforts to develop *Eucalyptus* as a bioenergy crop have been undertaken. In Hawaii, untended 3-5 year old coppice stands averaged stem wood weights of 2-3 dry tons/ac/year, and a 5 year old stand produced 6 dry tons/ac/year.

Efforts to develop *Eucalyptus* as an energy crop are underway in Florida. *E. amplifolia* can be grown from central Florida northward to about 50 miles inland from the Gulf Coast. Yields of 11.2 dry ton/ac/year for *E. amplifolia* have been attained in north Florida. *E. grandis* is more suitable for production in southern Florida and yields of 16.1 dry ton/ac/year have been achieved there. Efforts are underway to produce Eucalyptus on phosphate mining land as a means of remediating the land. As part of a feasibility study for co-firing Eucalyptus for electricity generation, it was estimated that sufficient quantities could be delivered to a local utility at a cost of $18.34/green ton (assumes 60% moisture) or $2.66/million Btu. Harvest was assumed to occur using a conventional feller-buncher and harvest represented 70% of the total cost. Currently, approximately 6,000 hectares of *Eucalyptus grandis* are commercially produced in Florida.

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## Microalgae

Microalgae are microscopic aquatic organisms that use sunlight to convert carbon dioxide ($CO_2$) and water into organic compounds (i.e. phosynthesis). Microalgae include of number of different kinds of organisms and are generally classified based on pigmentation, life cycle, and basic cellular structure. Microalgae classes include diatoms (such as phytoplankton in oceans), green algae (e.g., pond scum), bluegreen algae (freshwater algae), and golden algae (fresh water algae). They are among the most primitive forms of plants. Their photosynthetic mechanism is similar to higher plants, but they are much more efficient at converting sunlight into organic materials because of their simple cellular structure and efficient access to water, $CO_2$, and nutrients, due to their aquatic nature (Sheehan, 1998).

Much of the interest in using microalgae as a biomass feedstock is to produce biodiesel, although other fuels (e.g., ethanol) and bioproducts could also be produced. Because of their high photosynthetic efficiency, microalgae are capable of producing 30 times the amount of oil per unit area of land compared to terrestrial oilseed crops (Sheehan, 1998).

Efforts are underway to identify and develop microalgae species that can not only produce high levels of lipids (fats and oils), but which can also grow under a wide range of environmental conditions (i.e., temperature extremes, salinity, and pH). Additional issues related to the use of microalgae are scaling up the size of the production facilities, and finding uses for the material left over after the oil has been extracted (Kho, 2006).

From 1996 to 1998, the U.S. Department of Energy funded research to develop biodiesel production from high lipid microalgae. The process used open, shallow ponds constructed in a race-track configuration. The source of the $CO_2$ used by the microalgae was flue gas from electric facilities that used fossil fuels. The $CO_2$, water, and microalgae were circulated around the pond with nutrients continuously added and microalgae continuously harvested. Oil was then extracted from the microalgae and then converted into biodiesel. For a number of technical, economic, and funding reasons, the program was discontinued, but other public and private sector institutions have continued to work on developing microalgae (Sheehan, 1998).

Systems other than open ponds are being developed. These include closed bioreactors consisting of closely spaced membranes, which permit high levels of light penetration. Systems compatible with non-electrical utility industrial processes (such as ethanol production facilities) that produce waste $CO_2$ are also be developed (Sklar, 2006).

In the U.S., Greenfuel Technology Corporation is testing its process at an electric utility in the southwest U.S.  The company reports that its results suggest the potential for annual yields of 5,000 to 10,000 gallons of biodiesel/acre (Greenfuel, 2007).

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