2

Raw Material Resource Base

The United States has abundant forests and croplands, favorable climates, accessible capital, and sophisticated technologies for a strong biobased industry. As agriculture productivity and silviculture productivity continue to increase, more biomass will be available to support a biobased industry. Advances in biotechnology will keep a continuous supply of new crops flowing into the marketplace. The United States has substantial resources to invest in a carbon economy based on renewable resources.

Conversion of industrial production to the use of renewable resources will require abundant and inexpensive raw materials. The three potential sources of such materials are agricultural and forest crops and biological wastes (e.g., wood residue or corn stover). The amount of each resource available for biobased production will depend on how much these crops are consumed by competing uses and how much land is dedicated to crops grown for industrial uses. The land and other agricultural resources of the United States are sufficient to satisfy current domestic and export demands for food, feed, and fiber and still produce ample raw materials for biobased industrial products except for massive fuel production.

SILVICULTURE CROPS

Forests are a major source of raw materials for the production of wood products. The amount of land supporting the nation's forests has remained relatively constant since 1930 (USDA, 1995). Heightened public interest for forest preservation has led to government policies that support conversion of federal forest lands to special uses such as parks and wildlife areas that prohibit timber production. As these competing uses for national federal forests intensify, increases in timber harvesting on private forestlands will have to offset timber production declines on U.S. public lands (NRC, 1997; USDA, 1995).

Productivity from silviculture and timber harvests has increased on forest lands. The average volume of standing timber per hectare (800 x 10^9 cubic feet in 1991) is now 30 percent greater than it was in 1952 (USDA, 1995). Forest growth nationally has exceeded harvest since the 1940s—a trend that was accelerating until very recently. In 1991 forest growth exceeded harvest by 22 percent, even though the harvest was 68 percent greater than in 1952. More recently (1986 to 1991), the proportion of timber harvested from the total forested land has increased, primarily as a result of increased harvesting on industrial forestlands. The U.S. Department of Agriculture (USDA) Forest Service is forecasting further increases in the nationwide volume of harvested timber from slightly over 16 billion cubic feet in 1991 to nearly 22 billion cubic feet in 2040 (USDA, 1995).

Production capacity of timbered forestland may be underused. Softwood residues are generally in high demand as feedstocks, but hardwood timber residues have less demand and fewer competing uses. Underutilized wood species include southern red oak, poplar, and various small-diameter hardwood species (USDA, 1995).

In the future forestlands may be planted to silviculture crops for use in bioenergy production. Bioenergy crops may confer a number of benefits such as low maintenance requirements, high yields, and environmental advantages. The USDA and the U.S. Department of Energy (DOE) have field tested several short-rotation woody crop species (harvested on a cycle of 3 to 10 years), including hybrid poplar, black locust, eucalyptus, silver maple, sweet gum, and sycamore. Certain woody feedstocks have yields averaging 4.5 to 7.5 dry tons per acre per year—two to three times the yields normally achieved by traditional forest management in the United States. Even higher yields occur under certain conditions. Recent results show potential yields that consistently reach 8.9 dry tons per acre per year in several locations (Bozell and Landucci, 1993).

AGRICULTURAL CROPS

Cropland acreage is the third major use of land in the United States. The most notable trend in cropland use is the movement of cropland from crop idling programs into crop use and out again (ERS, 1997a). Four principal crops—corn, wheat, soybean, and hay—accounted for nearly 80 percent of all crops harvested in 1996. Current use of commodity crops for industrial uses is low. Coproduction of grain crops such as corn for both food and ethanol fuels will help reduce any future conflicts inherent in allocating renewable resources to two important human needs: food and fuel.

The United States has long been the world's largest producer of coarse grains. Recent data indicate that domestic grain production makes up approximately 67 percent of the world's grain supply (USDA, 1997a). In 1998 the United States exported over 37 million metric tons of corn grain (ERS, 1999). According to the USDA, U.S. feed grain production is projected to increase steadily through 2005. Expected increases in production are due to increasing yields, except for corn, where more acreage also accounts for gains in some years. Corn yields are expected to increase 1.7 bushels per acre per year based on the long-term trend. Corn plantings are expected to remain at or above 80 million acres throughout the next decade (USDA, 1997a). Continuing gains in U.S. agricultural productivity will extend the resource base available for biobased crop production.

U.S. corn yield nearly tripled between 1950 and 1980 from an average of about 35 bushels per acre to over 100 bushels per acre (OTA, 1980). Based on these gains, analysts predicted that corn yields would exceed 120 bushels per acre by 1995. This has, in fact, occurred: the 1992 and 1994 corn yields exceeded 130 bushels per acre (NASS, 1994; USDA, 1997a). Of the 252 million metric tons of corn produced in the 1996 to 1997 marketing year, approximately 19 million metric tons (7 percent of the total corn grain production) were allocated to industrial uses (industrial starch, industrial alcohol, and fuel alcohol) (ERS, 1997b). To the extent that we understand the many factors contributing to crop yield, productivity increases in many cases will be enhanced by improvements in plant genetics, pest management, and soil quality. At the current rate of growth, another 19 million metric tons of corn could become available by the turn of the century.

Perennial grasses and legumes are being evaluated as potential energy crops (Hohenstein and Wright, 1994). These grasses include Bahia grass, Bermuda grass, eastern gama grass, reed canary grass, napiergrass, rye, Sudan grass, switchgrass, tall fescue, timothy, and weeping love grass. Legumes that have been tested include alfalfa, bird's-foot trefoil, crown vetch, flatpea, clover, and *Sericea lespedeza*. In 1992 about 150 million tons of hay (more than half of which was alfalfa and alfalfa mixtures) were harvested from 59 million acres of croplands in the United States (USDA, 1994). In 1994 hay was harvested from approximately 61 million acres in the United States (ERS, 1997a). Considerable preproduction research now focuses on the facile conversion of some of these materials into fermentable sugars. Thick-stemmed perennial grasses, such as energy cane and napiergrass, produce yields from 5.4 to 14.5 dry tons per acre per year. These are current yields and likely would increase following selection. They may one day be grown and used on a large scale.

ENHANCING THE SUPPLY OF BIOMASS

The amount of cropland that will actually be used to supply biobased processors depends on a demand for the final product, and the inputs used to make that product must be competitively priced. Industrial processors bid for corn and forages based on processing costs and product prices in the petrochemical and specialty chemical industries. Some industries that produce specialty starches and lactic acid plastics can bid grain and productive croplands away from food processors now. But some industrial products, such as grain-based ethanol, may not be able to compete with food producers even after considerable declines in grain or forage prices. Even with anticipated new technology, grain-based ethanol probably will not compete with petroleum fuels on a cost basis (Kane et al., 1989). Similarly, access to major commodity plastics markets, like ethylene, may require very low-cost feedstocks (Lipinsky, 1981). The amount of land devoted to crops for biobased industries will depend on economics, as tempered by agricultural policies.

Some resources that are not useful for food production may soon become more suitable for industrial products because processing technologies that use woody biomass are improving. Potential supplies from three sources—crop residues, wood wastes, and Conservation Reserve Program land—are discussed below. Other available biomass wastes (e.g., municipal solid waste) also may be potential sources of lignocellulosic materials. These reserves may provide the best odds for competitive production of biobased industrial products.

Waste Materials

The United States produces abundant wastes that are potential raw materials for biobased products. It is estimated that 280 million metric tons per year of biological wastes are currently available (refer to Table 2-1). Much of this is crop residues, predominantly from corn—about 100 million metric tons of corn residues are produced annually (Gallagher and Johnson, 1995). To a lesser extent, paper mill, wood, and municipal solid waste also are important. Approximately 5.6 million metric tons of unused wood residue is generated in all U.S. sawmills (Smith et al., 1994). Crop residues represent a major untapped source of carbon-rich raw materials available onsite at a low to negligible cost. However, expenses for collection, storage, and transport must be considered in using these bulky,

TABLE 2-1 Estimated Available Waste Biomass in the United States[a]

Feedstock	Quantity (1000 dry metric tons)
Recycled primary paper pulp sludge	3,400
Urban tree residue[b]	38,000
Mixed office paper	4,600
Sugarcane bagasse	700
Newsprint	11,200
Rice	2,700
Corn gluten feed	5,700
Spent brewers grains	1,100
Distillers' dried grains	1,800
Corn gluten meal	1,100
Small grain straw	0
Wood mill residue[c]	5,600
Corn stover[d]	100,000
Cotton gin waste[e]	15,000
Sulfite waste liquor[f]	61,000
Cheese whey from dairy[g]	28,000
Total	279,900

SOURCE: Rooney (1998).

[a] Available quantity estimates of various lignocellulosic resources as biobased feedstocks will vary with region and local soil conditions.

[b] Urban tree residue is a feedstock of heterogeneous quality available from many sources.

[c] Value of all unused wood mill residues from Smith et al. (1994).

[d] Corn stover estimate based on Gallagher and Johnson (1995). Calculations assume 30 percent residues left on soil. Some levels of corn stover may cost less than new crops because stover and grain are produced together making recovery of land costs unnecessary because they have already been accounted for in grain profit calculations.

[e] Cotton gin waste based on a density of 1 ton per acre. Data from personal communication with Ralph Hardy of the National Agricultural Biotechnology Council, September 21, 1998.

[f] Represents sulfite waste liquor generated in sulfite paper mills in the United States. Data from Morris and Ahmed (1992).

[g] Represents total amounts generated in sugar and cheese processing in 1990. Data from Morris and Ahmed (1992).

low-valued residues. Sufficient biological wastes exist to supply the carbon for all 100 million metric tons of organic carbon-based chemicals consumed annually in the United States as well as to provide part of the nation's fuel requirements (Morris and Ahmed, 1992). Production of industrial products from agricultural wastes can reduce competition for agricultural resources.

Conservation Reserve Program

There is potential that land idled by the Conservation Reserve Program (CRP) could be used to grow biobased crops. This federal program was initiated in 1986 to help owners and operators of highly erodible croplands conserve and improve the soil and water resources on their farms and ranches through long-term land retirement. The CRP provides monetary incentives for farmers to retire environmentally sensitive lands from crop production for 10 to 15 years and to convert them to perennial vegetation. The 1996 Federal Agricultural Improvement and Reform Act limited enrollment to 36.4 million acres through the year 2002 (ERS, 1997a).

Some CRP lands may be suitable for harvest of perennial grasses and energy crop production while preserving soil and wildlife habitat. Judicious harvesting on a fraction of CRP lands might be consistent with wildlife and wetlands preservation. Field-scale studies are under way to quantify changes in soil and water quality and native biodiversity due to production of biomass energy crops on former agricultural lands (Tolbert et al., 1997; Tolbert and Schiller, 1996). Grass production on CRP lands could enhance biomass supply: at least 46 million tons of additional feedstock would be available if one-half of CRP lands was available. This figure assumes low yields of biomass (approximately 2.5 tons per acre), and these yields could increase up to 10 tons per acre for some crops (e.g., switchgrass).

Land costs in the CRP are a barrier to the biobased industry. Land values are high because the federal government must at least match the opportunity of foregone profits from continued production of annual crops such as corn or wheat. Average rental costs under the 1997 CRP are about $40 per acre (Osborn, 1997). Without the CRP and with conservation requirements on these lands, biomass production might be competitive with lower land rental rates for pasture; comparable rental rates for midwestern pasture are about $20 per acre. If the rental rate for CRP lands fell to the pasture rate, the cost of producing switchgrass could decline; presently switchgrass production costs are about $40 per ton (Park, 1997). CRP revision for energy crop harvest is a contentious issue. Furthermore, some have argued that reduced land rental costs for energy crops are a de facto subsidy (Walsh et al., 1996). The potential of using CRP lands to grow biomass energy crops is a topic that merits further investigation.

The total biomass is sufficient to easily meet current demands for biobased organic chemicals and materials. High-value chemicals are not expected to require large acreages. Future demands for biobased commodity chemicals potentially can be met with biomass from waste resources and crops grown on some CRP lands. While biobased materials such as lumber, cotton, and wool do have substantial markets, these products now compete successfully for land resources.

Coproduction of human food and animal feed products such as protein with biobased products is expected to help prevent future conflicts between production of food and biobased fuels. Corn-based refineries, for example, yield protein for animal feed and oil, starch, fiber, and fuel alcohol products. In the case of pulp and paper mills, pulp, paper, lignin byproducts, and ethanol can be produced while recycling waste paper in a single system. Current demands for liquid fuel are being met with current production of corn grain. If policymakers chose to increase ethanol fuel production beyond the capacity for coproduction of food and liquid fuel, biobased crops grown for energy uses could compete for land with food production. Opportunities for coproduction of food, feed, liquid fuels, organic chemicals, and materials are described in more detail in Chapter 4.

FILLING THE RAW MATERIAL NEEDS OF A BIOBASED INDUSTRY

The foundation of a biobased industry depends on an abundant supply of plant materials. Raw materials such as starches, cellulose, and oil can already be extracted from plants for the production of biomaterials, chemicals, and fuels. The committee envisions that many more plant substances (e.g., biopolymers or chiral chemicals) may serve as raw materials for industrial applications in the future. While conventional breeding methods continue to play an important role in developing new crops and cultivars, genetic engineering of existing crops will greatly enhance the number and precision of such modifications and the variety of plant products available for industrial use. Introduction of new crops for biobased production will be limited without an adequate infrastructure for cultivar research, development, and commercialization.

Satisfying the raw material needs of expanding biobased industries will require crops with the following characteristics: contain biomolecules and biochemical systems with potential industrial applications; can be manipulated to produce desirable molecules; can sustain a high level of predictable raw material production; and are supported by an infrastructure for biomass harvesting, transfer, storage, and industrial processing.

Current Resources

Renewable resources have been used for a wide variety of industrial purposes. For example, silviculture crops have been used for many years as construction materials; wood can undergo additional processing to yield a variety of other products such as paper and textiles. Because agricultural and silvicultural crops are highly variable, plant parts become more valuable when they can be further separated into their biochemical components. In the long term, plant parts that can be converted to sugars for fermentation are likely to become a major feedstock for the production of biobased chemicals, fuels, and materials.

Woody Plant Parts (Lignocellulosics)

Woody plant parts are an abundant biological resource for the biobased industry. Wood is a complex material composed of carbohydrate and lignin polymers that are chemically and physically intertwined. Considerable energy is required to separate the wood polymers from each other. Much of the harvested wood is used for lumber, and both wood and other woody materials are used for pulp production.

Improvements in wood processing are leading to new biomaterials that may replace plastic products currently produced from petrochemical sources. For instance, improved resistance to insects and decay fungi, dimensional stability, hardness, and other properties result when wood is esterified, cross-linked, and impregnated (Stamm, 1964). Wood that has been plasticized by decrystallization and esterification can be further shaped by injection- and extrusion-molding processes. Although these processes are currently economically impractical, they might provide many new products from wood-flour and wood-fiber-reinforced thermoplastic composites in the future. Scientists and engineers will continue to refine industrial processes that can be used to produce useful biomaterials from wood.

Separated Plant Components

Plant matter contains hundreds of components that are useful inputs for biobased production. Plants are primarily carbohydrates (cellulose, other polysaccharides such as starch, and sugars), lignins, proteins, and fats (oils). Starch and sugar polymers are end products of photosynthesis and dominate a plant's carbohydrate reserves. Accessing these vast carbohydrate reserves will be key to maintaining a renewable source of raw materials that can substitute for petrochemicals.

Cellulose

Cellulose is a carbohydrate polymer composed of glucose and constitutes about 45 percent of woody plant parts. Cellulose can be isolated by pulping processes and then further processed to yield such chemicals as ethanol and cellulose ethers; cellulose acetate, rayon, and cellulose nitrate; cellophane; and other cellulosics. Many of these derivatives have only specialty applications because their cost is high relative to that of petrochemical-derived polymers.

Numerous sources of cellulose pulp can be used for chemical production. The primary source of wood cellulose pulp comes from conifer species (Smith et al., 1994), but hardwood uses have increased in the past two decades. Flax residue (flax tow) and kenaf are grown commercially for pulp production. In other countries, pulp is made from crop residues such as straw and sugarcane bagasse. Because of its dominating abundance in plants, cellulose will always be a primary feedstock of any biobased industry.

Hemicelluloses

Hemicelluloses are composed of carbohydrates based on pentose sugars (mainly xylose) as well as hexoses (mainly glucose and mannose). Hemicelluoses make up 25 to 35 percent of the dry weight of wood and agricultural residues; they are second only to cellulose in abundance among carbohydrates. While use of hemicellulose is currently limited, quantities of hemicelluloses, pectins, and various other plant polymers are abundant in residues and have great potential in the production of chemicals and materials.

Lignin

Lignin is a phenylpropane polymer that holds together cellulose and hemicellulose components of woody plant matter. Lignin constitutes about 15 to 25 percent of the weight of lignocellulose. Lignin has not yet been used as a raw material for industrial use in large quantities. Concerted attempts by pulp and paper research laboratories to develop new markets for byproduct lignins have had only limited success (Bozell and Landucci, 1993). Production of low-molecular-weight compounds from kraft lignin (phenols in particular) similarly has not yet proved commercially competitive. This reflects the chemical complexity of lignin and its resistance to depolymerization. Nevertheless, a recent DOE study concluded that pyrolysis of lignocellulosics (lignin, cellulose, and hemicellulose plant tissues) could make production of phenolics and anthraquinone from lignin competitive, and the potential also exists to produce benzene, toluene, and xylenes from lignin via pyrolysis (Bozell and Landucci, 1993). Lignocellulose pretreatment receives special attention in this report because it will be a key step for realizing the presently untapped potential of abundant lignocellulosic materials found in wood and other perennial crops.

Starch

Starch is the principal carbohydrate reserve of plants. Corn starch currently is a primary feedstock for starch-based ethanol, plastics, loose-fill packing material, adhesives, and other industrial products. Approximately 600 million bushels of corn went into production of industrial products during the marketing year 1995 to 1996; of that total, 395 million bushels were used to produce fuel ethanol (ERS, 1996b). While the supply of corn starch has been sufficient to meet current demands, primarily anhydrous motor fuel grade and industrial ethanol, other supplies of sugar feedstocks are being evaluated to meet anticipated increases in demand for oxygenated fuels and chemicals.

Proteins

Proteins are the primary means of expressing the genetic information coded in DNA. These polymers are based on building blocks of amino acid monomers whose sequence is predetermined by a genetic template. The sequence diversity of proteins is responsible for the wide array of functions performed by proteins in living organisms (OTA, 1993) (see Box 2-1). A variety of plant proteins might one day be commercially exploited as materials, but current understanding of the structural properties of most plant proteins is limited.

One of the few well-understood plant proteins is zein, an abundant protein in corn seeds. Zein makes up 39 percent of the kernel protein, or about 4 percent of the kernel weight. The protein has several properties of industrial interest, such as the ability to form fibers and films that are tough, glossy, and grease and scuff resistant. Zein resists microbial attack and cures with formaldehyde to become essentially inert. In addition, it is water insoluble and thermoplastic.

The USDA Northern Regional Research Laboratory in Peoria, Illinois, developed zein into a textile fiber in the late 1940s. Scientists generated the fiber by dissolving zein in alkali, extruding the solution through spinnerets into an acid coagulating bath, and then curing the product with formaldehyde. Zein fibers are strong, washable, and dyeable and possess other desirable properties. The Virginia-Carolina Corporation commercialized zein-based fiber as "Vicara," producing about 5 million pounds in 1954. However, the company discontinued manufacture shortly thereafter, perhaps because of the advent of comparable synthetic fibers. Zein's main use today is as a water-impermeable coating for pharmaceutical tablets, nuts, and candies. It also functions as a cork binder for gaskets and bottle-cap liners, a binder in ink, a varnish, and a shellac substitute. The advantageous properties of zein suggest that its industrial usefulness merits reexamination (Wall and Paulis, 1978). There is potential to alter