CHAPTER 4

Virgin Biomass Production

I. INTRODUCTION

The manufacture of synfuels or energy products from virgin biomass requires that suitable quantities of biomass chosen for use as energy crops be grown, harvested, and transported to the end user or conversion plant. For continuous, integrated biomass production and conversion, provision must be made to supply sufficient feedstock to sustain conversion plant operations. Since at least 250,000 botanical species, of which only about 300 are cash crops, are known in the world, it would seem that biomass selection for energy could be achieved rather easily. This does not necessarily follow simply from the multiplicity of biomass species that can be considered for energy usage. Compared to the total known botanical species, a relatively small number are suitable for the manufacture of synfuels and energy products. The selection is not easily accomplished in some cases because of the discontinuous nature of the growing season and the compositional changes that sometimes occur on biomass storage. Many parameters must be studied in great detail to choose the proper biomass species or combination of species for operation of the system. They concern such matters as growth area availability; soil type, quality, and topography; propagation and planting procedures; growth cycles; fertilizer, herbicide, pesticide, and other chemical needs; disease resistance of monocultures; insolation, temperature, precipitation and irrigation needs; preharvest management, crop management, and harvesting methods; storage stability of the harvest; solar drying in the field versus in-plant drying in connection with conversion requirements; growth area competition for food, feed, fiber, and other end uses; the possibilities and potential benefits of simultaneous or sequential growth of two or more biomass species for synfuels and foodstuffs; multiple end uses; and transport to the conversion plant gate or end-use site.

As mentioned in earlier chapters, biomass chosen for energy applications, in the ideal case, should be high-yield, low-cash-value species that have short growth cycles and that grow well in the area in which the biomass energy system is located. Fertilization requirements should be low and possibly nil if the species selected fix ambient nitrogen, thereby minimizing the amount of external chemical nutrients that have to be supplied to the growth areas. In areas having low annual rainfall, the species grown should have low consumptive water usage and be able to utilize available precipitation at high efficiencies. For terrestrial energy crops, the requirements should be such that they can grow well on low-grade soils so that the best classes of agricultural or forestry land are not needed. After harvesting, growth should commence again without the need for replanting by vegetative or coppice growth. Surprisingly, several biomass species meet many of these idealized characteristics and appear to be quite suitable for energy applications. This chapter addresses the important factors that affect biomass production for energy applications.

II. CLIMATIC AND ENVIRONMENTAL FACTORS

The biomass species selected as energy crops and the climate must be compatible to sustain operation of the energy or fuel farm under human-controlled conditions. Wild stands of biomass are also amenable to harvesting as energy crops and are still the primary sources of virgin biomass feedstocks because large-scale energy and fuel farms in which dedicated biomass energy crops are grown have not yet been established. The few attempts that have been made to design, build, and operate such farms have not been too successful. The compatibility of biomass and climate is, nevertheless, essential to ensure that these systems can ultimately be operated at a profit on a commercial scale. The three primary climatic factors that have the most influence on the productivity and yields of an indigenous or transplanted biomass species are insolation, precipitation, and temperature. Natural fluctuations of these factors remove them from human control, but the information compiled over the years in meteorological records and from agricultural and forestry practice supplies a valuable data base from which biomass energy systems can be conceptualized and developed. Of these three factors, precipitation has the greatest impact because droughts can wreak havoc on biomass growth. Fluctuations in insolation and temperature during normal growing seasons do not adversely affect biomass growth as much as insufficient water. Ambient carbon dioxide (CO_2) concentration and the availability of macronutrients and micronutrients are also important factors in biomass production.

A. INSOLATION

The intensity of the incident solar radiation at the earth's surface is one of the key factors in photosynthesis, as shown in Chapter 3. Except in a few rare cases, natural biomass growth will not occur without solar energy. Isolation varies with geographic location, time of day, and season of the year, and as is well known, it is high in the tropics and near the equator. The approximate changes of insolation with latitude are illustrated in Table 4.1 (Brinkworth, 1973), and Fig. 4.1 shows how the mean annual insolation varies at the earth's surface with geographic location (Crutchfield, 1974). A more quantitative summary of average total daily insolation values over the continental United States is shown in Table 4.2 (U.S. Dept. of Commerce, 1970). At a given latitude, the incident radiation is not constant and often exhibits large changes over relatively short distances. Although several environmental factors influence biomass productivity, there is usually a relatively good correlation between the annual yields of dry biomass per unit area and the average insolation value (see Table 3.1). All other factors being equal, it is generally true that the higher the insolation, the higher the annual yield of a particular energy crop provided it is adapted to the local environment. C_4 biomass species often exhibit higher productivities in terms

TABLE 4.1 Insolation at Various Latitudes for Clear Atmospheres[a]

		Maximum		Minimum		Average[b]	
Location	Latitude	W/m^2	Btu/ft^2-day	W/m^2	Btu/ft^2-day	W/m^2	Btu/ft^2-day
Equator	0°	315	2400	236	1800	263	2000
Tropics	23.5°	341	2600	171	1300	263	2000
Mid-earth	45°	355	2700	70.9	540	210	1600
Polar circle	65.5°	328	2500	0	0	158	1200

[a] Brinkworth (1973).
[b] Yearly total divided by 365.

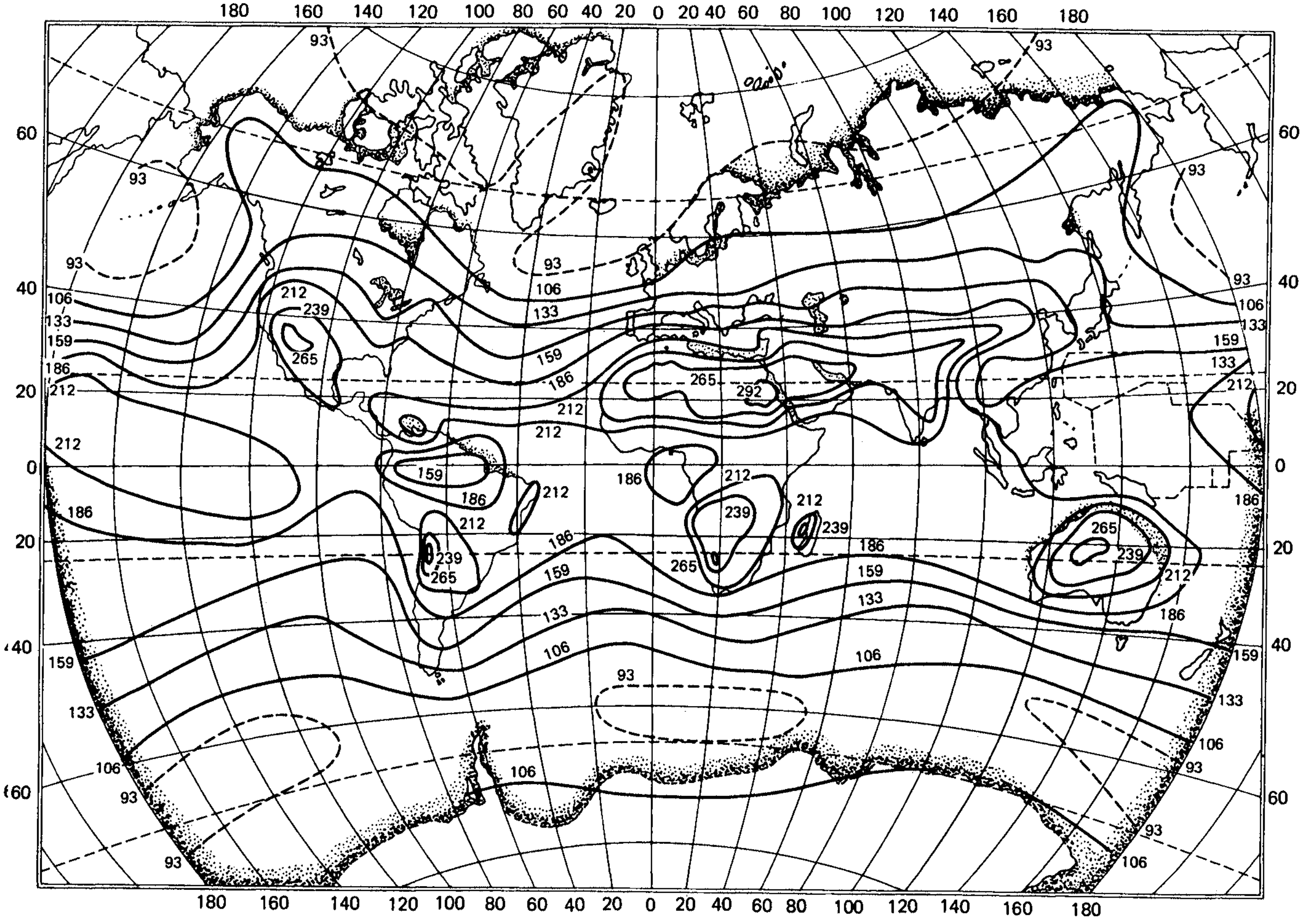

FIGURE 4.1 Mean annual insolation at earth's surface (W/m^2)

TABLE 4.2 Average Daily Insolation for Selected U.S. Cities[a]

Location	January (W/m²)	April (W/m²)	July (W/m²)	October (W/m²)	Annual (W/m²)
Arizona—Tucson	146	289	288	208	229
California—Fresno	93	290	338	187	229
Florida—Lakeland	135	260	247	189	210
Indiana—Indianapolis	90	188	242	120	157
Louisiana—Lake Charles	109	215	236	175	191
Minnesota—St. Cloud	76	178	275	104	157
Montana—Glasgow	72	190	299	118	175
Nevada—Ely	108	257	288	176	210
Oklahoma—Oklahoma City	81	212	264	155	183
Texas—San Antonio	113	198	286	182	199
Vermont—Burlington	76	182	208	100	146
Virginia—Sterling	91	173	233	113	159
Washington—Seattle	37	179	276	98	151

[a] U.S. Dept. of Commerce (1970).

of growth rates and annual yields because of their capability to utilize incident solar radiation at higher efficiencies for photosynthesis.

B. PRECIPITATION

Precipitation as rain, or in the form of snow, sleet, or hail, depending on atmospheric temperature and other conditions, is governed by movement of air and is generally abundant wherever air currents are predominately upward. The greatest precipitation should therefore occur near the equator. The average annual precipitation in the continental United States is shown in Fig. 4.2 (Visher, 1954); Table 4.3 (U.S. Dept. of Commerce, 1995) is a summary of the average monthly and annual precipitation at different locations in the United States. The average annual rainfall is about 79 cm.

The moisture needs of aquatic biomass are presumably met in full because growth occurs in liquid water, but the growth of terrestrial biomass is often water-limited. The annual requirements for good growth have been found for many biomass species to be in the range 50 to 76 cm (Roller *et al.*, 1975). Some crops, such as wheat, exhibit good growth with much less water, but they are in the minority. Without irrigation, water is supplied during the growing season by the water in the soil at the beginning of the season and by

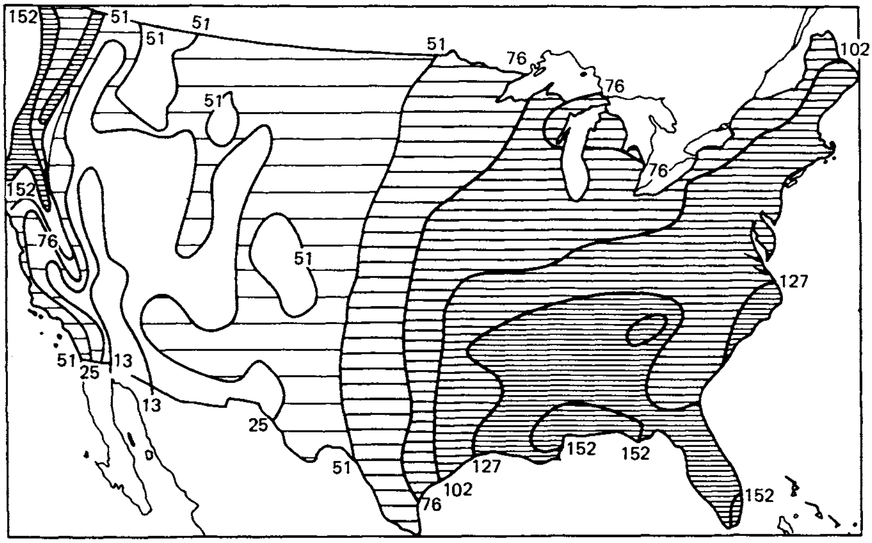

FIGURE 4.2 Normal annual precipitation (cm).

rainfall. Figure 4.3 illustrates the normal precipitation recorded in the continental United States during the growing season, April to September (Visher, 1954). This type of information and the established requirements for the growth of terrestrial biomass can be used to divide the United States into precipitation regions as shown in Fig. 4.4 (Visher, 1954). The regions that are more productive for biomass generally correlate with the precipitation regions, as shown in Figs. 4.5 and 4.6 (Visher, 1954). It should be realized, though, that rainfall alone is not quantitatively related to productivity of terrestrial biomass because of the differences in soil characteristics, water evaporation rates, and infiltration. Also, as suggested in Fig. 4.5, certain areas that have low precipitation can be made productive through irrigation. Some areas of the country that vary widely in precipitation as a function of time, such as many western states, will produce moderate biomass yields and often sufficient yields of cash crops without irrigation to justify commercial production.

The transpiration of water to the atmosphere through biomass stomata is proportional to the vapor pressure difference between the atmosphere and the saturated vapor pressure inside the leaves. Transpiration is obviously affected by atmospheric temperature and humidity. The internal water is essential for biomass growth. The efficiency of utilizing this water (water-use efficiency, WUE) has been defined as the ratio of biomass accumulation to the water consumed, expressed as transpiration or total water input to the system. Analysis of the transpiration phenomenon and the possibilities for manipulation

TABLE 4.3 Average Monthly and Annual Precipitation for Selected U.S. Cities, 1961 to 1990[a]

Location	January (cm)	April (cm)	July (cm)	October (cm)	Annual (cm)
Alaska—Juneau	11.5	7.0	10.6	19.9	137.9
Arizona—Phoenix	1.7	0.6	2.1	1.7	19.5
California—Los Angeles	6.1	1.8	0.03	0.9	30.5
California—San Francisco	11.0	3.5	0.08	3.1	50.0
Colorado—Denver	1.3	4.3	4.9	2.5	39.1
Florida—Miami	5.1	7.2	14.5	14.3	142.0
Hawaii—Honolulu	9.0	3.9	1.5	5.8	55.9
Indiana—Indianapolis	5.9	9.4	11.4	6.7	101.4
Louisiana—New Orleans	12.8	11.4	15.5	7.7	157.2
Minnesota—Minneapolis	2.4	6.1	9.0	5.6	71.9
Montana—Great Falls	2.3	3.6	3.1	2.0	38.6
Nevada—Reno	2.7	1.0	0.7	1.0	19.1
Oklahoma—Oklahoma City	2.9	7.0	6.6	8.2	84.7
Texas—Dallas-Fort Worth	4.6	8.9	5.6	5.8	85.6
Vermont—Burlington	4.6	7.0	9.3	7.3	87.6
Virginia—Norfolk	9.6	7.8	12.9	8.0	113.4
Washington—Seattle	13.7	5.9	1.9	8.2	94.5

[a] U.S. Dept. of Commerce (1995).

of WUE have led some researchers to conclude that biomass production is inextricably linked to biomass transpiration. Agronomic methods that minimize surface runoff and soil evaporation, and biochemical alterations that reduce transpiration in C_3 plants, have the potential to increase WUE. But for water-limited regions, the fact remains that without additional water, the research results indicate that these areas cannot be expected to become regions of high biomass yields (Sinclair, Tanner, and Bennett, 1984). Irrigation and full exploitation of humid climates are of highest priority in attempting to increase biomass yields in these areas.

C. TEMPERATURE

Most biomass species grow well in the United States at temperatures between 15.6 and 32.3°C (60 and 95°F). Typical examples are corn, kenaf, and napier grass. Tropical grasses and certain warm-season biomass have optimum growth

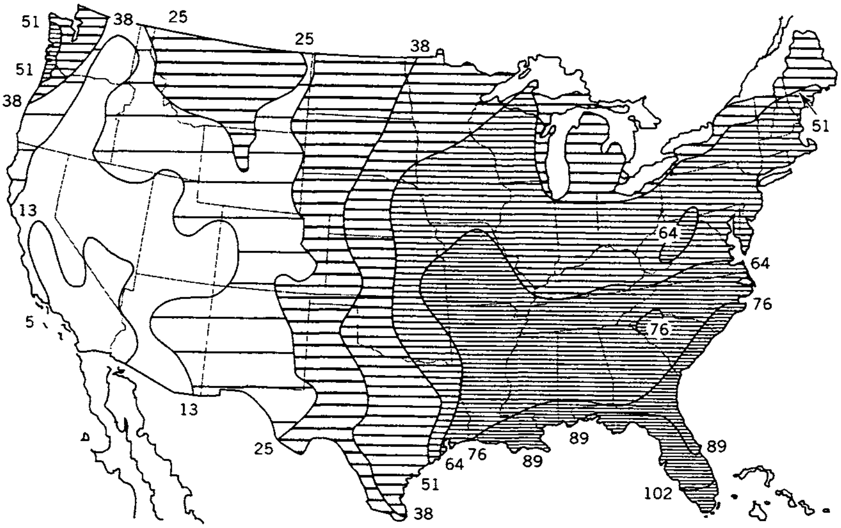

FIGURE 4.3 Normal precipitation during growing season April to September (cm).

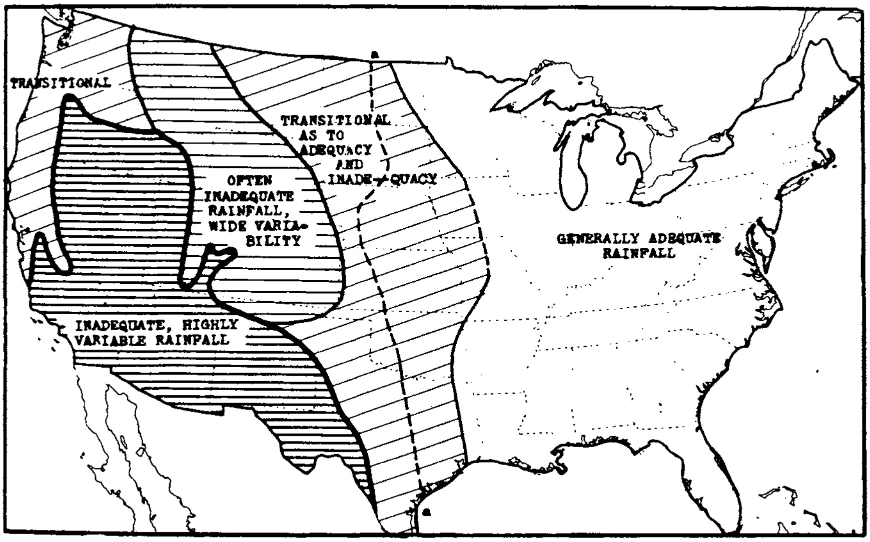

FIGURE 4.4 Precipitation regions.

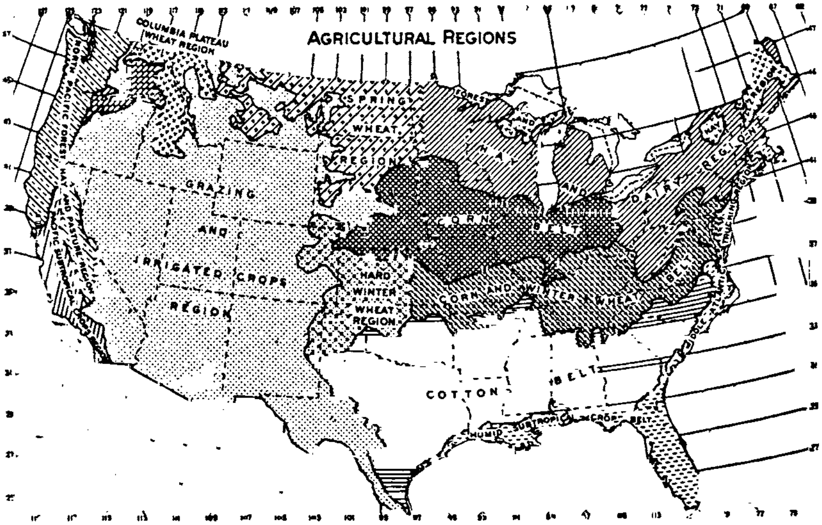

FIGURE 4.5 Agricultural regions.

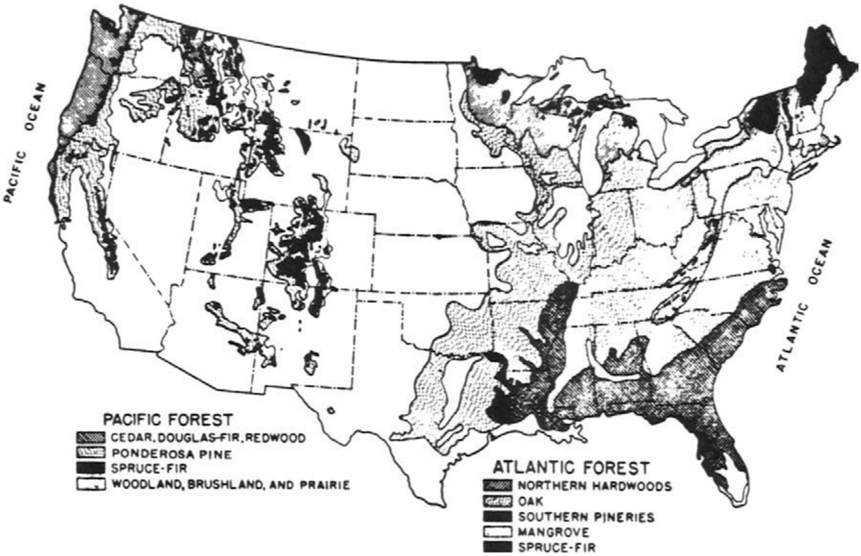

FIGURE 4.6 Forestland regions.

temperatures in the range 35 to 40°C (95 to 104°F), but the minimum growth temperature is still near 15°C (Ludlow and Wilson, 1970). Cool-weather biomass such as wheat may show favorable growth below 15°C, and certain marine biomass such as the giant brown kelp only survive in water at temperatures below 20 to 22°C (North, 1971). The average number of days per year in the continental United States where the temperature is less than 6.1°C (43°F) and essentially no biomass growth occurs are shown in Fig. 4.7 (Visher, 1954). Table 4.4 is a summary of average monthly and annual temperature fluctuations with time and location in the United States (U.S. Dept. of Commerce, 1995). The growing season is clearly longer in the southern portion of the country. In some areas such as Hawaii, the Gulf states, southern California, and the southeastern Atlantic states, the temperature is usually conducive to biomass growth most of the year.

The effect of temperature fluctuations on net CO_2 uptake is illustrated by the curves in Fig. 4.8 (El-Sharkawy and Hesketh, 1964). As the temperature increases, net photosynthesis increases for cotton and sorghum to a maximum value and then rapidly declines. Ideally, the biomass species grown in an area should have a maximum rate of net photosynthesis as close as possible to the average temperature during the growing season in that area.

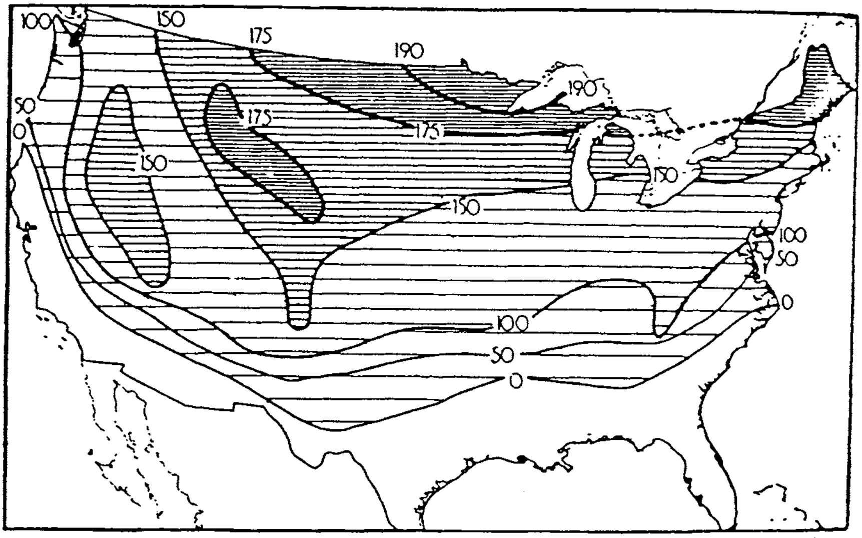

FIGURE 4.7 Annual number of days with temperature less than 6.1°C (43°F) and little or no biomass growth.

TABLE 4.4 Average Monthly and Annual Temperature for Selected U.S. Cities, 1961 to 1990[a]

Location	January (°C)	April (°C)	July (°C)	October (°C)	Annual (°C)
Alaska—Juneau	−4.3	4.3	13.3	5.7	4.8
Arizona—Phoenix	12.0	21.1	34.2	23.6	22.6
California—Los Angeles	13.8	15.6	20.6	19.3	17.2
California—San Francisco	9.3	13.1	17.1	16.1	13.9
Colorado—Denver	−1.3	9.0	23.1	10.8	10.2
Florida—Miami	19.6	24.0	28.1	25.7	24.4
Hawaii—Honolulu	22.7	24.3	26.9	26.4	25.1
Indiana—Indianapolis	−3.6	11.3	24.1	12.6	11.3
Louisiana—New Orleans	10.7	20.3	27.7	20.6	20.1
Minnesota—Minneapolis	−11.2	8.0	23.1	9.3	7.2
Montana—Great Falls	−6.0	6.4	20.1	8.6	7.1
Nevada—Reno	0.5	9.2	22.0	10.4	10.4
Oklahoma—Oklahoma City	2.2	15.8	27.8	16.7	15.6
Texas—Dallas-Fort Worth	6.3	18.6	29.4	13.4	18.6
Vermont—Burlington	−8.7	6.6	21.4	8.8	7.0
Virginia—Norfolk	3.9	13.9	25.7	16.2	15.1
Washington—Seattle	4.5	9.6	18.6	11.6	11.1

[a] U.S. Dept. of Commerce (1995).

D. AMBIENT CARBON DIOXIDE CONCENTRATION

Many studies show that higher concentrations of CO_2 than normally present in air will promote more carbon fixation and increase biomass yields. In confined environmentally controlled enclosures such as hothouses, carbon dioxide-enriched air is often used to stimulate growth. In large-scale, open-air systems such as those envisaged for biomass energy farms, this is not practical. For aquatic biomass production, CO_2 enrichment of the water phase may be a potentially attractive method of promoting biomass growth if CO_2 concentration is a limiting factor, since biomass growth often occurs by uptake of CO_2 from both the air and liquid phase near the surface.

For some high-growth-rate biomass species, the CO_2 concentration in the air among the leaves of the plant is often considerably less than that in the surrounding atmosphere. Photosynthesis may be limited by the CO_2 concentrations under these conditions when wind velocities are low and insolation is high.

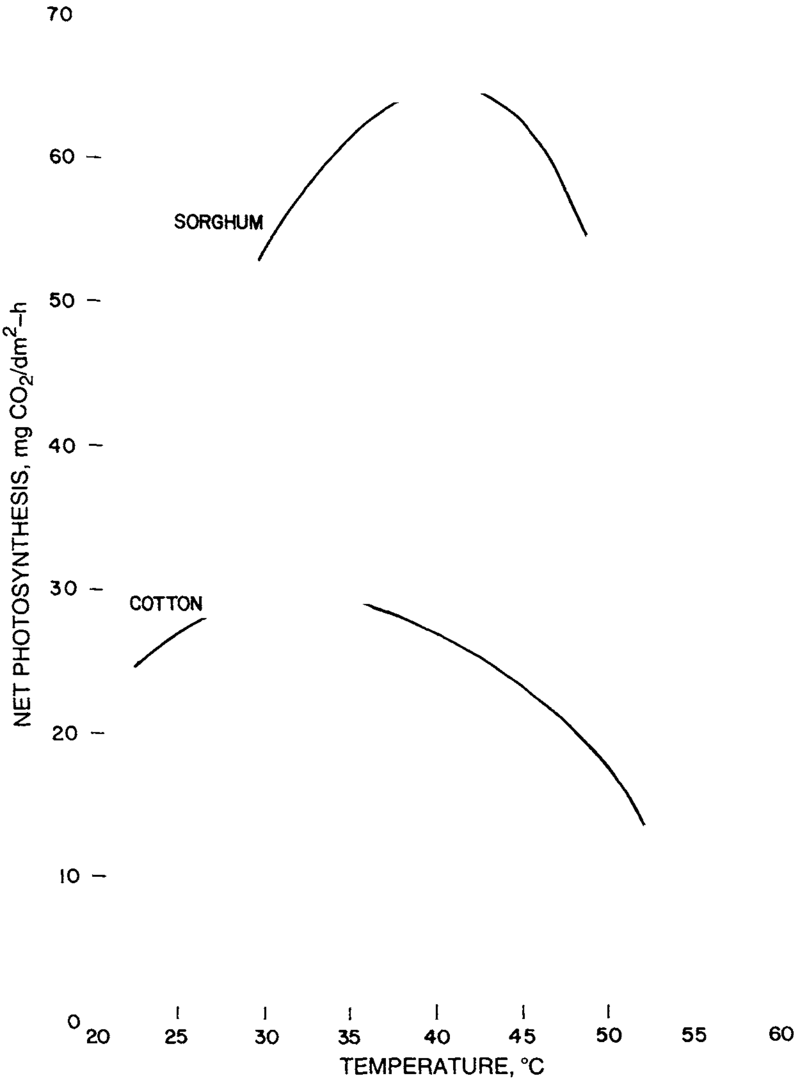

FIGURE 4.8 Effect of temperature on net photosynthesis for sorghum and cotton leaves.

E. NUTRIENTS

All living biomass requires nutrients other than carbon, hydrogen, and oxygen to synthesize cellular material. Major nutrients are nitrogen, phosphorus, and potassium; other nutrients required in lesser amounts are sulfur, sodium, magnesium, calcium, iron, manganese, cobalt, copper, zinc, and molybdenum. The last five nutrients, as well as a few others not listed, are sometimes referred to as micronutrients because only trace quantities are needed to stimulate growth. For terrestrial biomass, all of these elements are usually supplied by the soil, so eventually the soil's natural nutrients are depleted if they are not replaced through fertilization. Some biomass species, such as the legumes, are able to meet all or part of their nitrogen requirements through fixation of ambient nitrogen. Marine biomass such as giant brown kelp use the natural nutrients in ocean waters. Freshwater biomass such as water hyacinth is often grown in water rich in nutrients such as municipal wastewaters. The growth of the plant is stimulated and at the same time, the influent wastewater is stabilized because its components are taken up by the plant as nutrients. So-called luxuriant growth of water hyacinth on biosolids, in which more than the needed nutrients are removed from the wastewater, can be used as a substitute wastewater treatment method.

Whole plants typically contain 2 wt % N, 1 wt % K, and 0.5 wt % P, so at a yield of 20 t/ha-year, harvesting of the whole plant without return of any of the plant parts to the soil corresponds to the annual removal of 400 kg N, 200 kg K, and 100 kg P per hectare. This illustrates the importance of fertilization, especially with these macronutrients, to maintain soil fertility. Indeed, biomass growth is often nutrient-limited and yield correlates with increased dose rates. An example is U.S. corn production from 1945 to 1970. Nitrogen fertilizer applications were increased from 8 kg/ha to 125 kg/ha over this period; the corresponding edible corn yields increased from 2132 to 5080 kg/ha (Krummel, 1976). Average nitrogen fertilizer applications for production of wheat, rice, potato, and brussels sprouts are about 73, 134, 148, and 180 kg/ha, respectively, in the United States (Krummel, 1976). Much of the success of the "green revolution" is claimed to be the result of greater fertilizer applications. Estimates of balanced fertilizers needed to produce various land biomass species are shown in Table 4.5 (Roller *et al.*, 1975). Note that alfalfa does not require added nitrogen because of its nitrogen-fixing ability. It is estimated that this legume can fix from about 130 to 600 kg of elemental nitrogen per hectare annually (Evans and Barber, 1977).

Normal weathering processes that occur in nutritious soils release nutrients, but they are often not available at rates that promote maximum biomass yields. Fertilization is usually necessary to maximize yields. Since nitrogenous fertilizers are currently manufactured from fossil fuels, mainly natural gas, and since fertilizer needs are usually the most energy intensive of all the inputs in a biomass production system, a careful analysis of the integrated biomass production-conversion system is necessary to ensure that net energy production is positive. Trade-offs between synfuel outputs, nonsolar energy inputs,

TABLE 4.5 Estimated Fertilizer Requirements of Selected Biomass[a]

Biomass	Required mass per unit weight of whole dry plant, kg/dry t			
	N	P_2O_5	K_2O	CaO
Alfalfa	0	12.3	34.0	20.7
Corn	11.8	5.7	10.0	0
Kenaf	13.9	5.0	10.0	16.1
Napier grass	9.6	9.3	15.8	8.5
Slash pine (5 year)	3.8	0.9	1.6	2.3
Potato	16.8	5.3	28.3	0
Sugar beet	18.0	5.4	31.2	6.1
Sycamore	7.3	2.8	4.7	0
Wheat	12.9	5.3	8.4	0

[a] Roller *et al.* (1975).

and biomass yields are required to operate a system that produces only energy products.

III. AVAILABILITY OF LAND AND WATER AREAS FOR BIOMASS PRODUCTION

A. LAND AREAS

The availability of land suitable for production of terrestrial biomass can be estimated by several techniques. For the United States, one method relies on a land capabilities classification scheme in which land is divided into eight classes (Table 4.6) (U.S. Dept. of Agriculture, 1966). Classes I to III are suitable for cultivation of many kinds of crops; Class IV is suitable only for limited production; and Classes V to VIII are useful only for permanent vegetation such as grasses and trees. The U.S. Department of Agriculture surveyed nonfederal land usage for 1987 in terms of these classifications and arrived at the breakdown shown in Table 4.7 (U.S. Dept. of Agriculture, 1989). Out of about 568 million ha, which corresponds to about 60% of the 50-state area, about 43% of the land (246.4 million ha) was in Classes I to III, 13% (75.6 million ha) was in Class IV, and 43% (246.3 million ha) was in Classes V to VIII. The actual usage of this land at the time of the survey is shown in Table 4.8 (U.S. Dept. of Agriculture, 1989). This table shows that of all the land judged suitable for cultivation in Classes I to III, only about 58% of it was

TABLE 4.6 Land Capability Classification by United States Department of Agriculture[a]

Class	Description
I	Few limitations that restrict use.
II	Moderate limitations that reduce the choice of plants or require moderate conservation practice.
III	Severe limitations that reduce the choice of plants or require special conservation practices, or both.
IV	Very severe limitations that reduce the choice of plants or require very careful management, or both.
V	Not likely to erode, but other limitations, impractical to remove, that limit use largely to pasture, range, woodland, or wildlife habitat.
VI	Severe limitations that make soils generally unsuited to cultivation and limit their use largely to pasture or range, woodland, or wildlife habitat.
VII	Severe limitations that make soils unsuited to cultivation and that restrict use largely to pasture or range, woodland, or wildlife habitat.
VIII	Limitations that preclude use for communical plants and restrict use largely to recreation, wildlife habitat, water supply, or to esthetic purposes.

[a] U.S. Dept. of Agriculture (1966).

TABLE 4.7 Land Capability Classification of Nonfederal Rural Land by U.S. Department of Agriculture in 1987[a]

Land class	Area (10^6 ha)	% of total
I	13.47	2.37
II	117.36	20.65
III	115.53	20.33
IV	75.59	13.30
V	13.55	2.38
VI	106.71	18.78
VII	114.86	20.21
VIII	11.22	1.97
Total	568.29[b]	

[a] Adapted from U.S. Dept. of Agriculture (1989). Data are for the 48 contiguous states, Hawaii, and the Caribbean area.

[b] This area is 72.35% of the land surveyed, or 60.55% of the total 50-state area excluding the outlying areas (938.50 million ha). The federal land, water, and developed land areas are 17.43, 2.14, and 3.34% of the total 50-state area, respectively.

TABLE 4.8 Summary of U.S. Nonfederal Rural Land Usage by Use Type, 1987[a]

Land class	Cropland (10^6 ha)	Pastureland (10^6 ha)	Rangeland (10^6 ha)	Forest (10^6 ha)	Minor uses (10^6 ha)	Total (10^6 ha)
I	11.58	0.82	0.17	0.66	0.23	13.47
II	77.31	12.81	6.58	18.00	2.66	117.36
III	54.28	16.00	18.76	24.26	2.23	115.53
IV	18.60	10.30	21.62	23.56	1.51	75.59
V	1.16	1.86	1.99	7.52	1.03	13.55
VI	6.56	6.84	53.34	37.34	2.63	106.71
VII	1.59	3.91	58.40	46.88	4.08	114.86
VIII	0.035	0.067	1.68	1.40	7.81	11.00
Other	0	0	0	0	2.08	2.08
Total	171.12	52.60	162.56	159.62	24.25	570.15
Percent	30.01	9.22	28.51	28.00	4.25	

[a] Adapted from U.S. Dept. of Agriculture (1989). Totals may not be precise summations because of rounding. Cropland is land used for production of crops for harvest alone or in rotation with grasses and legumes. Pastureland is land used for production of adapted, introduced, or native species in a pure stand, grass mixture, or a grass–legume mixture. Rangeland is land on which the vegetation is predominantly grasses, grass-like plants, forbs, or shrubs suitable for grazing or browsing. Forest is land that is at least 10% stocked by trees of any size or formerly having had such tree cover and not currently developed for nonforest use. Other land is land such as farmsteads, strip mines, quarries, and lands that do not fit into the other land use category.

actually used as cropland, the locations of which are shown in Table 4.9 (U.S. Dept. of Agriculture, 1989). Also, the combined areas of pasture, range, and forestlands made up about 66% of the total nonfederal lands. This survey suggests that there is ample opportunity to produce biomass for energy applications on nonfederal land that is not used for foodstuffs production. Large areas of land in Classes V to VIII not suitable for cultivation would appear to be available also for biomass energy applications, and sizable areas in Classes I to IV that are not being used for crop production seem to be available. Land now used for crop production could also be considered for simultaneous or sequential growth of biomass for foodstuffs and energy. Portions of the federally owned lands, which are not included in this survey, might also be dedicated to biomass energy applications. Careful design and management of land-based biomass production areas could very well result in improvement or upgrading of lands to higher land capability classifications.

B. WATER AREAS

The production of marine biomass in the ocean, even on the largest scale envisaged for energy applications, would require only a very small fraction of

TABLE 4.9 Summary of U.S. Cropland Capability Classification by Region, 1987[a]

Region	No. of states	Classes I–III (10^6 ha)	Class IV (10^6 ha)	Classes V–VIII (10^6 ha)	Total (10^6 ha)
Northeast	11	5.567	0.875	0.375	6.817
Appalachian	5	7.252	1.138	0.712	9.102
Southeast	4	5.915	0.786	0.372	7.073
Delta states	3	7.897	0.561	0.342	8.800
Corn Belt	5	34.868	2.210	0.846	37.924
Southern Plains	2	15.314	1.532	0.760	17.606
Northern Plains	4	32.688	3.746	2.256	38.690
Lake states	3	15.255	1.865	0.745	17.865
Mountain states	8	11.674	3.981	2.247	17.902
Pacific	3	6.578	1.860	0.593	9.031
Hawaii, Caribbean	1	0.166	0.051	0.096	0.313
Total	49	143.17	18.60	9.34	171.12
Percent of total		83.7	10.9	5.5	

[a]Adapted from U.S. Dept. of Agriculture (1989). Alaska excluded.

the available ocean areas. For example, it is estimated that, depending on biomass yield, a square area about 320 to 540 km on each edge off the coast of California may be sufficient to produce enough giant brown kelp for conversion to methane to supply all U.S. natural gas needs (Bryce, 1978). This is a large area, but it is very small when compared with the total area of the Pacific Ocean. Also, the benefits to other marine life from large kelp plantations have been well documented. Any conflicts that might arise would be concerned primarily with ocean traffic. With the proper plantation design for marine biomass and precautionary measures to warn approaching ships, it is expected that marine biomass growth could be sustained over long periods.

Freshwater biomass could in theory be grown on the 20 million ha of fresh water in the United States. But there are several difficulties that mitigate against large-scale freshwater biomass energy systems. About 80% of the fresh water in the United States is located in the northern states, whereas several of the freshwater biomass species considered for energy applications require a warm climate such as that found in Gulf states. The freshwater areas suitable for biomass production in the southern states, however, are much smaller than those in the North, and the density of usage is higher in southern inland waters. Overall, these characteristics make small-scale aquatic biomass production systems more feasible for energy applications. In the future, it may be advisable to examine the possibility of constructing large man-made lakes for this purpose, but this does not seem practical at this time except possibly where an aquatic biomass species is used for wastewater treatment.

IV. SELECTION OF VIRGIN BIOMASS SPECIES FOR ENERGY APPLICATIONS

A. Terrestrial Biomass

Much effort to evaluate terrestrial biomass for energy applications has been expended (for the United States, see Hohenstein and Wright, 1994; Ferrell, Wright, and Tuskan, 1995). In general, this work has been aimed at selecting high-yield biomass species, characterizing their physical and chemical properties, defining their growth requirements, and rating their energy use potential. Several species have been proposed specifically for energy usage, whereas others have been recommended for multiple uses, one of which is as an energy resource. The latter case is exemplified by sugarcane; bagasse, the fibrous material remaining after sugar extraction, is used in several sugar factories as a boiler fuel. It is probable that most land-based biomass plantations operated for energy production or synfuel manufacture will also yield products for nonenergy markets. Large-scale biomass energy plantations that produce single energy products will probably be the exception rather than the rule. Land-based biomass for energy production can be divided into forest biomass, grasses, and cultivated plants.

Forest Biomass

About one-third of the world's land area is forestland. Broad-leaved evergreen trees are a dominant species in tropical rain forests near the equator (Spurr, 1979). In the northern hemisphere, stands of coniferous softwood trees such as spruce, fir, and larch dominate in the boreal forests at the higher latitudes, while both the broad-leaved deciduous hardwoods such as oak, beach, and maple and the conifers such as pine and fir are found in the middle latitudes. Silviculture, or the growth of trees, is practiced by five basic methods: exploitative, conventional extensive, conventional intensive, naturalistic, and short-rotation (Spurr, 1979). The exploitative method is simply the harvesting of trees without regard to regeneration. The conventional extensive method is the harvesting of mature trees so that natural regeneration is encouraged. Conventional intensive silviculture is the growing and harvesting of commercial tree species in essentially pure stands such as Douglas fir and pine on tree farms. The naturalistic method has been defined as the growth of selected mixed tree species, including hardwoods, in which the species are selected to match the ecology of the site. The last method, short-rotation silviculture (short-rotation woody crop or SRWC, short-rotation intensive culture or SRIC), has been suggested as the most suitable method for energy applications. In this technique, trees that grow quickly are harvested every few years, in contrast to once every 20 or more years. Fast-growing trees such as cottonwood, red alder, and aspen are intensively cultivated and mechanically harvested every 3 to 6 years when they are 3 to 6 m high and only a few centimeters in diameter. The young trees are converted into chips for further processing or direct fuel use and the small remaining stems or stumps form new sprouts by vegetative growth (coppicing) and are intensively cultivated again. SRWC production affords dry yields of several tons of biomass per hectare annually, often without large energy inputs for fertilization, irrigation, cultivation, and harvesting, so that the energy balance is positive.

It should be noted that although the prime purpose is to produce wood fiber for the manufacture of paper products, the pulp and paper companies have operated large tree plantations that yield energy as a by-product for decades. Heat, steam, and electricity are produced from wood wastes and also black liquor, which is generated in the paper manufacturing process (Chapter 5). Almost two-thirds of all renewable fuels consumed by the U.S. industrial sector is accounted for by the industry's use of black liquor (U.S. Dept. of Energy, 1995). The pulp and paper industry produces well over half of its own energy needs and clearly has a great interest in sustained-yield forestry. In the United States, several pulp and paper companies are developing SRWC technology to provide improved methods for supplying fiber to pulp mills and by-product energy (Stokes and Hartsough, 1994). In 1994, approximately 20,000 ha of SRWC systems were operated in the United States by the pulp and paper industry; 40,000 to 80,000 ha were projected to be operated by the year 2000.

Historically, trees are important resources and still serve as major energy resources in many developing countries. No fewer than 1.5 billion people in developing countries derive at least 90% of their energy requirements from wood and charcoal, and at least another billion people meet at least 50% of their energy needs this way (National Academy of Sciences, 1980). Hundreds of species in the seven genera *Acacia, Casuarina, Eucalyptus, Pinus, Prosopis, and Trema* are used as fuelwood in developing countries (Little, 1980). Several studies of temperate forests indicate productivities from about 9 to 28 t/ha-year, while the corresponding yields of tropical forests are higher, ranging from about 20 to 50 t/ha-year (Nichiporovich, 1967). These yields are obtained using conventional forestry methods over long periods of time, 20 to 50 years or more. Productivity is initially low in a new forest, slowly increases for about the first 20 years, and then begins to decline. Coniferous forests will grow even in the winter months if the temperatures are not too low; they do not exhibit the yield fluctuations characteristic of deciduous forests.

One of the tree species that has been studied in great detail as a renewable energy resource is the eucalyptus (Mariani, 1978), evergreen hardwood trees that belong to the myrtle family, Myrtaceae, and the genus *Eucalyptus*. There are approximately 450 to over 700 identifiable species in the genus. The eucalyptus is a rapidly growing tree native to Australia and New Guinea, and is widely grown in the United States, especially in Southern California and Hawaii for a variety of construction purposes. High-density plantings (17,790 trees/ha) in Southern California of *E. grandis* harvested twice annually have been reported to yield in excess of 22 dry t/ha-year (Sachs, Gilpin, and Mock, 1980). It appears to be a prime candidate for energy use because it reaches a size suitable for harvesting in about 7 years. Several species have the ability to coppice after harvesting, and as many as four harvests can be obtained from a single stump before replanting is necessary. In several South American countries, eucalyptus trees are converted to charcoal and used as fuel. Eucalyptus wood has also been used to power integrated sawmill, wood distillation, and charcoal-iron plants in western Australia. Several large areas of marginal land in the United States may be suitable for establishing eucalyptus energy farms. These areas are in the western and central regions of California and the southeastern United States.

Various species and hybrids of the genus *Populus* are some of the more promising candidates for SRWC growth and harvesting as an energy resource (Sajdak *et al.*, 1981). The group has long been cultivated in Europe and more recently in the eastern United States and Canada. *Populus* hybrids are easily developed and the resulting progeny are propagated vegetatively using stem cuttings. Consequently, there are hundreds of numbered or named clones established throughout the eastern United States. Summaries of record SRWC small-plot yields for *Populus* hybrids have shown production levels of 15-20 dry t/ha-year (Hansen, 1988) and yields of 30-40 dry t/ha-year have been projected as attainable goals through genetic engineering (Ranney, Wright, and Layton, 1987). SRWC growth of hybrid poplar clone D-01 has been reported to afford yields of biomass that range as high as 112-202 green t/ha-year (56-101 dry t/ha-year at 50 wt % moisture) (Dula, 1984). These results were reported with very high-density plantings that have been termed woodgrass in which the crop is grown like grass and is harvested several times each growing season. However, there is some dispute regarding the benefits of woodgrass growth vs SRWC growth (Wright *et al.*, 1989). Several investigators have not been able to reproduce these results (*cf.* DeBell and Clendenen, 1991), although the high-density planting technique seems to have some potential benefits.

It was concluded from early studies that deciduous trees are preferred over conifers for the production of woody biomass for conversion to biofuels (InterTechnology Corp., 1975). Conifers are used as fuel in many parts of the world, including the United States, but the long-term research effort to develop woody species as dedicated energy crops emphasizes mostly deciduous species (*cf.* Ferrell *et al.*, 1993; Wright, 1994; Ferrell, Wright, and Tuskan, 1995). Several deciduous species can be started readily from clones, resprout copiously and vigorously from their stumps at least five or six times without loss of vigor, and exhibit rapid initial growth. They can also be grown on sites with slopes as steep as 25%, where precipitation is 50 cm or more per year. It has been estimated that yields between about 18 and 22 dry t/ha-year are possible on a sustained basis almost anywhere in the Eastern and Central time zones in the United States from deciduous trees grown in dense plantings. Table 4.10 lists deciduous trees that were judged in early work to have desirable growth characteristics for plantation culture and that have been shown to grow satisfactorily at high planting densities for short and repeated harvest cycles.

Grasses

Grasses are very abundant forms of biomass (U.S. Dept. of Agriculture, 1948). About 400 genera and 6000 species are distributed all over the world and grow in all land habitats capable of supporting higher forms of plant life. Grasslands cover over one-half the continental United States, and about two-thirds of this land is privately owned. Grass, as a family (Gramineae), includes the great fruit crops, wheat, rice, corn, sugarcane, sorghum, millet, barley, and oats. Grass also includes the many species of sod crops that provide forage or pasturage for all types of farm animals. In the concept of grassland agriculture, grass also includes grass-related species such as the legumes family—the clovers, alfalfas, and many others. Grasses are grown as farm crops, for decorative purposes, for preserving the balance of productive capacity of lands by crop rotation, for controlling erosion on sloping lands, for the protection of water sheds, and for the stabilization of arid areas. Many advances in grassland agriculture have been made since the 1940s through breeding and the use of improved species of grass, alone or in seeding mixtures; cultural practices, including amending the soil to promote herbage growth best suited for specific purposes; and the adoption of better harvesting and storage techniques. Until the mid-1980s, very little of this effort had been directed to energy applications. A few examples of energy applications of grasses can be found such as the combustion of bagasse for steam and electric power, but many other opportunities exist that have not been developed.

Perennial grasses have been suggested as candidate feedstocks for conversion to synfuels. Most perennial grasses can be grown vegetatively, and they reestab-

TABLE 4.10 Representative Deciduous Trees for Plantation Culture and Locations Where They Have Been Shown to Grow Well in North America in Managed Plantings[a]

Locality state/province	Hybrid poplar	Aspen and hybrids	Black cottonwood	Red alder	Sycamore	Pin cherry	Plains cottonwood	Eastern cottonwood	Silver maple	European black alder	Green ash	Sweetgum	Eucalyptus
Alabama					X			X		X	X	X	X
Florida													X
Georgia					X						X	X	X
Illinois								X		X			
Indiana								X					
Kansas						X		X	X				
Louisiana								X					
Minnesota		X											
Mississippi					X			X					
Nebraska								X					
New Hampshire		X				X							
North Dakota							X						
Ohio										X			
Pennsylvania	X												
Texas								X					
Washington	X		X	X									
Wisconsin	X	X											
British Columbia				X									
Manitoba		X											
Nova Scotia	X												
Ontario	X												
Saskatchewan	X												

[a] InterTechnology Corp. (1975).

lish themselves rapidly after harvesting. Also, more than one harvest can usually be obtained per year. The warm-season grasses are preferred over the cool-season grasses because their growth increases rather than declines as the temperature rises to its maximum in the summer months. In certain areas, rainfall is adequate to permit harvesting every 3 to 4 weeks from late February into November, and yields between about 18 and 24 t/ha-year of dry grasses may be obtainable in managed grasslands. Some tropical and semitropical grasses are very productive and can yield as high as 50 to 60 t/ha-year on good sites (Westlake, 1963). The tropical fodder grass *Digitaria decumbens* has been grown at yields of organic matter as high as 85 t/ha-year (Westlake, 1963). Table 4.11 lists some promising grasses that have been proposed as energy resources in the United States (Cushman and Turhollow, 1991).

An example of a tropical grass that has been grown commercially as a combination foodstuff and fuel crop for many years is sugarcane (*Saccharum*

TABLE 4.11 **Average Annual Yields of Most Productive Herbaceous Species in Field Trials in U.S. Southeast and Midwest/Lake States**[a]

Biomass type and species	Southeast (dry t/ha-year)[b]	Midwest/Lake states (dry t/ha-year)[b]
Annuals		
Warm-season		
Sorghums[c]	0.2-19.0	1.9-29.1
Cool-season		
Winter rye[d]	0.0-7.2	2.4-6.1
Perennials[e]		
Warm-season		
Switchgrass[d]	2.9-14.0	2.5-13.4
Weeping lovegrass[d]	5.4-13.7	
Napiergrass-energy canes[c]	20.4-28.3	
Cool-season		
Reed canary grass[d]		2.7-10.8
Legumes		
Alfalfa		1.6-17.4
Flatpea	2.1-12.9	3.9-10.2
Sericea lespedeza	1.8-11.1	

[a] Cushman and Turhollow (1991).
[b] Averaged by site; data are for range of sites.
[c] Thick-stem grass.
[d] Thin-stem grass.
[e] Productivity rates after 1- to 2-year establishment period.
[e] Productivity rates after 1- to 2-year extablishment period.

spp.), but rising production costs, alternative sweeteners, and the nebulous mixture of changing social, political, and agricultural policy issues have not been kind to insular sugar planters (Alexander, 1993). A great deal of information has been accumulated about sugarcane, and it might well be used as a model tropical herbaceous crop for other biomass energy systems. It grows rapidly and produces high yields; the fibrous bagasse is used as boiler fuel for the generation of electric power; and sugar-derived ethanol is used as a motor fuel in gasoline blends (gasohol). Sugarcane plantations and the associated sugar processing and ethanol plants are in reality biomass fuel farms. About one-half of the organic material in sugarcane is sugar and the other half is fiber. Total cane biomass yields have been reported to range as high as 80 to 85 dry t/ha-year. Normal cultivation provides yields of about 50 to 59 dry t/ha-yr (Westlake, 1963). Studies on sugarcane managed specifically as an energy crop have been underway in Puerto Rico for several years. "First-generation energy cane" consisting of conventional varieties managed for optimal growth with irrigation averaged 186 green t/ha-year of whole cane including detached trash, whereas second generation yields exceeded 269 green t/ha-year (Alexander, 1983). At an average of 40 wt % dry matter, these yields range from 74 to 108 dry t/ha-year. Presuming the energy content of energy cane is about 18.5 GJ/dry t, the energy yields correspond to 1369 to 1998 GJ/ha-year, or the equivalent of 232 to 338 BOE/ha-year, a very high yield.

In moderate climates, switchgrass (*Panicum virgatum*) has been recommended as one of the model biomass energy crops for North America because of its high yield potential, adaptation to marginal sites, and tolerance to water and nutrient limitations (Sanderson *et al.*, 1995). It is a warm-season grass native to much of North America and is a major species in tall prairie grasses. Average yields are reported to range from 5.5 to 11.3 dry t/ha-year in the midwestern and eastern United States (Wright, 1994). In the southwestern United States, evaluation of eight switchgrass cultivars showed that for six locations in Texas, single harvests of fertilized plots of the Alamo cultivar afforded the highest average yields, 10.7 to 15.7 dry t/ha-year (Sanderson *et al.*, 1995).

Other productive grasses that have been given serious consideration as raw materials for the production of energy and synfuels include the perennials Reed canary grass, tall fescue, crested wheatgrass, weeping lovegrass, and Bermuda grass, the annual sorghum and its hybrids, and others. It is apparent that there are many grasses and related biomass species that can be considered for energy applications. They have many of the desirable characteristics needed for terrestrial biomass energy systems.

Other Cultivated Crops

Many other terrestrial biomass species have been proposed as renewable energy resources for their high-energy components that can be used as fuels, for the components capable of conversion to biofuels and chemicals, or for the contained energy (*cf.* Buchannan and Otey, 1978; Cherney *et al.*, 1989; DeLong *et al.*, 1995; Gavett, Van Dyne, and Blase, 1993; Klass, 1974; McLaughlin, Kingsolver, and Hoffmann, 1983; Nemethy, Otvos, and Calvin, 1981; O'Hair, 1982; Schneider, 1973; Shultz and Bragg, 1995; Stauffer, Chubey, and Dorell, 1981; Taylor, 1993). Among them are kenaf (*Hibiscus cannabinus*), an annual plant reproducing by seed only; sunflower (*Helianthus annuus* L.), an annual oil seed crop grown in several parts of North America; *Eurphorbia lathyris*, a sesquiterpene-containing plant species that grows in the semiarid climates of the Southwest and California; Buffalo gourd (*Curcurbita foetidissima),* a perennial root crop native to arid and semiarid regions of the southwestern United States; other root crops such as Jerusalem artichoke (*Helianthus tuberosus*), fodder beet (*Beta vulgaris*), and cassava (*Manihot esculenta*); alfalfa (*Medicago sativa*), a perennial legume that grows well on good sites in many parts of North America; soybean (*Glycine max*) and rapeseed (*Brassica campestris*), oilseed crops that produce high-quality oil and protein; and many other biomass species that are potentially suitable as renewable energy resources or multipurpose crops including energy and biofuels. Kenaf, for example, is highly fibrous and exhibits rapid growth, high yields, and high cellulose content. It is a pulp crop and is several times more productive than pulpwood trees. Maximum economic growth usually occurs in less than 6 months, and consequently two croppings may be possible in certain regions of the United States. Without irrigation, heights of 4 to 5 meters are average in Florida and Louisiana, but 6-m plants have been observed under near-optimum growth conditions. Yields as high as 45 t/ha-year have been observed on experimental test plots in Florida, and it has been suggested that similar yields could be achieved in the Southwest with irrigation. Another example is the sunflower, which is a good candidate for biomass energy applications too because of its rapid growth, wide adaptability, drought tolerance, short growing season, massive vegetative production, and adaptability to root harvesting. Dry yields have been projected to be as high as 34 t/ha per growing season. Rapeseed is another example; its seeds normally yield 38 to 44 wt % high quality protein and over 40 wt % oil, which affords high-quality biodiesel fuel at the rate of 750 to 900 L/ha-year on extraction and transesterification. Still another example is alfalfa, a well-known and widely-planted herbaceous crop that offers environmental and soil conservation advantages when grown as a 4-year segment in a 7-year rotation with corn and soybeans. With alfalfa yields of about 9 dry t/ha-year and the alfalfa leaf fraction sold as a high-value animal feed, the remaining alfalfa stem fraction can be used as feedstock for power production.

B. AQUATIC BIOMASS

The average net annual productivities of dry organic matter on good growth sites for terrestrial and aquatic biomass are shown in Table 4.12. With the exception of phytoplankton, which generally has lower net productivities,

TABLE 4.12 **Average Net Annual Biomass Yields on Fertile Sites**[a]

Average Net Yield (dry t/ha-year)	Climate	Ecosystem type	Remarks
1	Arid	Desert	Much more if hot and irrigated
2		Ocean phytoplankton	
2	Temperate	Lake phytoplankton	Little human influence
3		Coastal phytoplankton	Probably higher in some polluted estuaries
6	Temperate	Polluted lake phytoplankton	In agricultural and sewage runoffs
6	Temperate	Freshwater submerged macrophytes	
12	Temperate	Deciduous forests	
17	Tropical	Freshwater submerged macrophytes	
20	Temperate	Terrestrial herbs	Possibly more if grazed
22	Temperate	Agriculture—annuals	
28	Temperate	Coniferous forests	
29	Temperate	Marine submerged macrophytes	
30	Temperate	Agriculture—perennials	
30		Salt marsh	
30	Tropical	Agriculture—annuals	Including perennials in continental climates
35	Tropical	Marine submerged macrophytes	
38	Temperate	Reedswamp	
40	Subtropical	Cultivated algae	More if CO_2 supplied
50	Tropical	Rainforest	
75	Tropical	Agriculture—perennials, reedswamp	

[a] Westlake (1963).

aquatic biomass seems to exhibit higher net organic yields than most terrestrial biomass. Aquatic biomass species that are considered to be the most suitable for energy applications include the unicellular and multicellular algae, freshwater plants, and marine species.

Algae

Microalgae have long been under development as renewable energy resources and other useful products (Benemann and Weissman, 1993). Almost 20,000 species are known. Unicellular algae such as the species *Chlorella* and *Scenedesmus* have been produced by continuous processes in outdoor light at high photosynthesis efficiencies. *Chlorella* has been reported to be produced at a rate as high as 1.0 dry t/ha-day. This corresponds to an annual rate of 401dry t/ha-year presuming growth can be sustained (Retovsky, 1966). These figures are probably in error, but there is no theoretical reason why yields cannot achieve very high values because the process of producing algae can be almost totally controlled. Also, production is not composed only of surface growth. Algae are produced as slurries in lakes, ponds, and custom-designed raceways so that the depth of the biomass-producing area as well as plant yield per unit volume of water are important parameters. The nutrients for algae production can be supplied by municipal biosolids and other wastewaters. It should be pointed out that most unicellular algae are grown in fresh water, which tends to limit their energy applications to small-scale algae farms. The high water content of unicellular algae also tends to limit the conversion processes to biological methods. But this can be an advantage in some cases where the particular microalgae exudes triglycerides without cell destruction so that the product oil is continuously formed and can be easily recovered from the water surface.

Macroscopic multicellular algae, or seaweeds, have also been considered as renewable energy resources for many years. Some of the candidates are the giant brown kelp *Macrocystis pyrifera* (Bryce, 1978; North, 1971; North, Gerard, and Kubawabara, 1981), the red benthic alga *Gracilaria tikvahiae* (LaPointe and Hanisak, 1985; Ryther and DeBusk, 1982), and the floating, brown pelagic algae *Sargassum natans* and *S. fluitans* (LaPointe and Hanisak, 1985). Giant brown kelp has been studied in great detail and is harvested commercially off the California coast. Because of its high potassium content, giant brown kelp was used as a commercial source of potash during World War I and is used today as a commercial source of organic gums, thickening agents, and alginic acid derivatives. Off the East Coast, *Laminaria* seaweed is harvested for the manufacture of alginic acid derivatives. In tropical seas not cooled by upwelled water, species of the *Sargassum* variety of algae may be suitable as renewable energy sources. Several species of *Sargassum* grow naturally around reefs surrounding the Hawaiian Islands. Unfortunately, only a small amount of research has been done on *Sargassum* and little detailed information is available about this alga. A considerable amount of data on yields and growth requirements are available, however, on the *Macrocystis* and *Laminaria* varieties. Again, the very high water content of macroscopic algae suggests that biological conversion processes rather than thermochemical conversion processes should be used for synfuel manufacture. The manufacture of co-products from macroscopic algae, such as polysaccharide derivatives, along with biofuel might make it feasible to use thermochemical processing techniques on intermediate process streams.

Water Plants

The productivity of some salt marshes is similar to that of seaweeds. *Spartina alterniflora* has been grown at net annual yields of about 33 dry t/ha-year, including underground material, on optimum sites (Westlake, 1963). Other emergent communities in brackish water, including mangrove swamps, appear to have annual organic productivities of up to 35 t/ha-year (Westlake, 1963), but insufficient information is available to judge their value in biomass energy systems. Freshwater swamps are believed to be highly productive and offer opportunities for energy production. Both the reed *Arundo donax*, and bulrush *Scirpus lacustris* appear to produce 57 to 59 t/ha-year yields (Westlake, 1963); if these can be sustained, they should be suitable candidates for biomass energy usage. Cattail (*Typha* spp.) is a wetland biomass that has been proposed as an energy resource (Pratt and Andrews, 1980). It grows naturally in monocultures, is highly productive, has few insect pests, and can be grown on marginal lands. Managed stands are reported to yield 25 to 30 dry t/ha-year of cattail in the northern climates of the United States (Minnesota).

A strong aquatic biomass candidate for energy applications is the water hyacinth (*Eichhornia crassipes*) (Klass, 1974). This biomass species is highly productive, as might be expected because it grows in warm climates and has submerged roots and aerial leaves like reedswamp plants. It has been estimated that water hyacinth could be produced at rates up to about 150 t/ha-year if the plants were grown in a good climate, the young plants always predominated, and the water surface was always completely covered (Westlake, 1963). Some evidence has been obtained to support this growth rate (McGarry, 1971; Yount and Grossman, 1970). If such yields can be maintained on a steady-state basis, water hyacinth could possibly turn out to be a prime aquatic biomass candidate as a nonfossil carbon source for synfuels manufacture as well as other potential applications such as the manufacture of paper. Water hyacinth currently has no competitive uses and is considered to be an undesirable species on inland waterways. Many attempts have been made to rid navigable streams in Florida of water hyacinth without success; the plant is a very hardy, disease-resistant species (Del Fosse, 1977).

V. THE ECONOMICS OF VIRGIN BIOMASS PRODUCTION

A. Effects of Fossil Fuel Prices

The practical value of biomass energy ultimately depends on the costs of salable energy and biofuels to the end users. Consequently, many economic analyses have been performed on biomass production, conversion, and integrated biofuels systems. Conflicts usually abound when attempts are made to compare the results developed by two or more groups for the same biomass feedstock or biofuel because the methodologies are not the same. The assumptions made by each group are sometimes so different that valid comparisons cannot be made even when the same economic ground rules are employed. Comparative analyses, especially for hypothetical processes conducted by an individual or group of individuals working together, should be more indicative of the economic performance and ranking of biomass energy systems. However, several generalizations can be made that are quite important. The first is that fossil fuel prices are well documented and can be considered to be the primary competition for biomass energy. Table 4.13 summarizes U.S. tabulations of average, consumption-weighted, delivered fossil fuel prices by end-use sector in the mid-1990s (U.S. Energy Information Administration, December 1995). It is evident that the delivered price of a given fossil fuel is not the same to each end-use sector. The residential sector normally pays more for fuels than the other sectors, and the large end users pay less.

In the context of virgin biomass energy costs, dry woody and fibrous biomass species have an energy content on a dry basis of approximately 18.5 MJ/kg (7959 Btu/lb) or 18.5 GJ/t (16 MBtu/ton). For comparison purposes, if such types of biomass were available at delivered costs of $1.00/GJ ($1.054/MBtu), or $18.50/dry t ($16.78/dry ton), biomass on a strict energy content basis without conversion would cost less than most of the delivered fossil fuels listed in Table 4.13. The U.S. Department of Energy has set cost goals of delivered virgin biomass energy crops at $1.90-2.13/GJ ($2.00-2.25/MBtu), which corresponds to $35.15 to 39.41/dry t of virgin biomass (Fraser, 1993).

In the mid-1990s, few virgin biomass species were grown and harvested in the United States specifically for energy or conversion to biofuels, with the possible exceptions of feedstocks for fuel ethanol and a few tree plantations. This is not difficult to understand from an economic standpoint, especially if conversion costs are included. The nominal price of natural gas in the United

TABLE 4.13 U.S. Delivered Fossil Fuel Prices to End Users by Sector, 1993[a]

Fossil fuel	Residential ($/GJ)	Commercial ($/GJ)	Industrial ($/GJ)	Transportation ($/GJ)	Utility ($/GJ)
Coal	2.85	1.69	1.57		1.32
Natural gas	5.68	4.77	2.99		2.43
Petroleum	7.46	4.80	4.49	7.61	2.32
LPG	9.74	8.32	4.50	8.00	
Kerosine	7.18	5.07	5.06		
Distillate fuel	6.49	4.83	4.53	7.64	
Motor gasoline		8.90	8.60	8.60	
Aviation gasoline				7.82	
Jet fuel				4.07	
Residual fuel		2.61	2.29	1.88	
Heavy oil					2.25
Light oil					4.25
Petroleum coke					0.34

[a]Adapted from U.S. Energy Information Administration (December 1995). All figures are consumption-weighted averages for all states in nominal dollars and include taxes. Heavy oil includes Grade Nos. 4, 5, and 6. Light oil includes Grade Nos. 1 and 2, kerosine, and jet fuel.

States in 1994 at the wellhead (not end-use cost) was estimated to be $1.74/GJ ($1.83/MBtu) (U.S. Energy Information Administration, July 1995). For virgin biomass to compete as a feedstock for methane production on an equivalent basis, it would have to be grown, harvested, and gasified to produce methane at the same or lower cost. Assuming a gasification cost of zero and biomass conversion to substitute natural gas at 100% thermal efficiencies, both assumptions of which are totally unrealistic but which will help illustrate the best-case economics, the maximum market price of the biomass feedstock cost at the conversion plant gate including profit is then $32.19/dry t (at 18.5 GJ/dry t × $1.74/GJ). At an optimistic yield of 22.4 dry t/ha-year (10 dry ton/ac-year), the biomass producer who supplies the gasification plant with feedstock would then realize not more than $721/ha-year ($292/ac-year), a marginal amount to permit a net return on an energy crop without other incentives. Similar calculations for the production and conversion of virgin biomass to liquid petroleum substitutes at zero conversion cost and 100% thermal efficiencies at the average U.S. nominal wellhead price of crude oil of $13.19/bbl ($2.234/GJ) in 1994 (U.S. Energy Information Administration, July 1995) correspond to a maximum market price for virgin biomass feedstock of $41.33/dry t ($37.49/dry ton). The average price of hay, for example, received by farmers across the United States in 1994 was $95.59/t ($86.70/ton) (U.S. Dept. of Commerce, 1996). This indicates that the production of hay, and probably most grasses, as energy crops for conversion to liquid biofuels in direct competition with petroleum liquids was not economically feasible at that time. These simplistic calculations emphasize the effect of fossil fuel prices on dedicated biomass energy crops. Inclusion of gasification or liquefaction costs and conversion efficiency factors by the processor would result in still lower market prices that the processor would be willing to pay for biomass feedstocks. Negative feedstock costs (wastes), substantial by-product credits, captive uses, other markets and uses, environmental credits, and/or tax incentives would be needed to justify dedicated energy crop production on strict economic grounds.

B. BIOMASS PRODUCTION COSTS

An example of the detailed production costs in the mid-1990s of two commercial herbaceous crops grown without irrigation in the Corn Belt of the U.S. Midwest, the perennial alfalfa and the annual corn, is shown in Table 4.14 (University of Illinois Urbana-Champaign FaRM Lab, 1995). The economics are shown for the maintenance and harvesting of established alfalfa. The cost of planting in the first year is therefore excluded. For corn, no-till, no-rotation planting is used. This technique affords the lowest production cost, although attention must eventually be given to counteract any adverse effects on soil chemistry. Alfalfa has been proposed as a dedicated energy crop and corn is a commercial feedstock for fuel ethanol production. The analysis showed that the annual loss in nominal dollars was about $115/ha for alfalfa and $101/ha for corn. It is evident that at the production costs, reported yields, and market prices at that time, production of either crop could have led to a significant loss for the farmer. It is also evident that the major variable cost factors are chemicals and harvesting labor, and the major fixed cost is land rent.

It is immediately apparent from this assessment that situations can exist that would make alfalfa and corn production profitable. If the land is rented at much lower cost than indicated in Table 4.14 or is owned by the farmer with no outstanding debt, or the crops are grown on one or more family farms where resident labor is available, the economics can be quite different and favorable. Many scenarios can be envisaged that will improve the net return. The point is that what may appear to be uneconomic at first is subject to change when the details are analyzed and appropriate actions can be taken to improve profitability. The difficulty of accurately predicting market prices is another factor that complicates matters further. Indeed, it was only a few months after this analysis that the market price of corn began to increase at a rapid rate and to reach an all-time high of over $5.00/bu, which effectively

TABLE 4.14 Production Costs of Alfalfa Hay and Corn In Northern and Central Illinois[a]

Biomass		Alfalfa hay			Corn	
Production method		Maintain and harvest			No till and no rotation	
Time of costs		As of 11/11/95			As of 11/11/95	
Yield/growing season		9 t/ha-year			358 bu/ha-year	
Market price		\$77/t			\$2.35/bu[b]	
Variable costs	Unit/ha	Price/Unit	Cost/ha	Unit/ha	Price/Unit	Cost/ha
Fertilizer						
Anhydrous NH_3	0 kg	\$ 0.44	\$ 0.00	91 kg	\$ 0.44	\$ 83.84
P_2O_5	54 kg	\$ 0.53	\$ 28.61	67 kg	\$ 0.53	\$ 35.51
K_2O	224 kg	\$ 0.29	\$ 64.96	44 kg	\$ 0.29	\$ 12.76
Lime	1.12 t	\$ 14.33	\$ 16.05	1.12 t	\$ 14.33	\$ 16.05
Total fertilizer			\$ 109.62			\$ 148.16
Herbicides	Multiple	Multiple	\$ 59.30	Multiple	Multiple	\$ 84.02
Insecticides	Multiple	Multiple	\$ 12.36	Multiple	Multiple	\$ 34.59
Total pesticides			\$ 71.66			\$ 118.61
Seed	In-place	In-place	\$ 0.00	69.2 k	\$ 0.85	\$ 58.82
Crop insurance			\$ 0.00			\$ 12.36
Mach. fuel, repairs			\$ 0.00			\$ 12.36
Labor			\$ 0.00	0.72 h	\$ 10.00	\$ 7.20
Preharvest interest	3 mo.	9%	\$ 4.94	7 mo.	9%	\$ 19.77

Harvest costs						
Mach. fuel, repairs			$ 76.60			$ 14.45
Labor	15.39 h	$ 10.00	$ 153.90	3.14 h	$ 10.00	$ 31.40
Trucking			$ 0.00	358 bu	$ 0.02	$ 7.16
Drying			$ 0.00	3.3 L/bu	$ 0.042/L	$ 49.62
Storage			$ 0.00			$ 0.00
Total variable costs			$ 416.72			$ 479.91
Fixed costs						
Mach: cap., taxes, ins.		$ 81.91	$ 81.91		$ 153.27	$ 153.27
Land rent		$ 309.00	$ 309.00		$ 309.00	$ 309.00
Total fixed costs			$ 390.91			$ 462.27
Total costs			$ 807.63			$ 942.18
Total revenue			$ 693.00			$ 841.30
Net return (loss)						
Per ha-year over variable			$ 276.28			$ 361.39
Per unit over variable			$ 30.70/t			$ 1.01/bu
Per ha-year over total			($ 114.63)			($ 100.88)
Per unit over total			($ 12.74/t)			($ 0.28/bu)

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[a] Adapted from University of Illinois Urbana-Champaign FaRM Lab (1995).

[b] One bushel (0.03524 m^3) of corn is approximately 25.4 kg (56 lb).

doubled the farmer's revenue. Careful consideration of all cost factors is obviously necessary, but there is no approach to the elimination of all risk when growing a dedicated energy crop, or any other crop for that matter.

An economic analysis of the delivered costs of virgin biomass energy in 1990 dollars has been performed for candidate virgin herbaceous and woody biomass for different regions of the United States (Fraser, 1993). The analysis was done for each decade from 1990 to 2030 for Class I and II lands, but only the results for biomass grown on Class II lands for the years 1990 and 2030 are shown in Table 4.15. The total production costs for biomass were projected with discounted cash flow models, one for the herbaceous crops switchgrass, napier grass, and sorghum, and one for the short-rotation production of sycamore and hybrid poplar trees. The delivered costs are shown in Table 4.15 in 1990 \$/dry t and 1990 \$/MJ and are tabulated by region and biomass species.

TABLE 4.15 Estimated U.S. Delivered Costs for Candidate Biomass Energy Crops in 1990 and 2030[a]

	1990			2030		
Region and species	Yield (dry t/ha-year)	Cost (\$/dry t)	Cost (\$/GJ)	Yield (dry t/ha-year)	Cost (\$/dry t)	Cost (\$/GJ)
Great Lakes						
Switchgrass	7.6	104.07	5.26	15.5	61.32	3.60
Energy sorghum	15.5	62.56	3.17	30.9	36.79	2.16
Hybrid poplar	10.1	113.79	5.76	15.9	72.82	4.29
Southeast						
Switchgrass	7.6	105.89	5.36	17.3	52.91	3.11
Napier grass	13.9	63.72	3.22	30.9	33.31	1.96
Sycamore	8.1	88.61	4.49	14.3	53.19	3.13
Great Plains						
Switchgrass	5.4	74.32	3.77	10.3	44.05	2.59
Energy sorghum	6.3	91.73	4.65	13.7	48.07	2.83
Northeast						
Hybrid poplar	8.1	105.26	5.33	11.9	71.69	4.26
Pacific Northwest						
Hybrid poplar	15.5	66.69	3.56	23.8	44.73	2.63

[a] Adapted from Fraser (1993). Discounted cash-flow models account for the use of capital, income taxes, time value of money, and operating expenses. Real after-tax return is assumed to be 12.0%. Short-rotation model used for sycamore and poplar. Herbaceous model used for other species. The costs are in 1990 dollars. The yields in 1990 are on Class II lands. The average total field yields are for the entire region on prime to good soil, less harvesting and storage losses. The yields in 2030 are assumed to be attained through research and genetic improvements. Short-rotation woody crops (hybrid poplar and sycamore) are grown on 6-year rotations on six independent plots. Net income is negative for first 5 years for each SRWC plot.

The yield figures for 1990 were obtained by the analysts from the literature and the projected yields for 2030 were assumed to be achievable from continued research. The annual, dry biomass yields per unit area have a great influence on the final estimated costs, as would be expected. This analysis indicates that the lowest-cost energy crop of those chosen can be different for different regions of the country. A few of the biomass-region combinations appear to come close to providing delivered biomass energy near the U.S. Department of Energy cost goal. But realizing that there are many differences in the methodologies and assumptions used to compile the 1990 costs for delivered fossil fuels in Table 4.13 and delivered virgin biomass energy in Table 4.15, it appears that many of the biomass energy costs are competitive with those of fossil fuels in several end-use sectors, even without incorporating the yield improvements that are expected to evolve from continued research on biomass energy crops.

However, it is essential to recognize several other factors in addition to the basic cost of virgin biomass and its conversion when considering whether the economics are competitive with the costs of other energy resources and fuels. Some potential biomass energy feedstocks have negative values; that is, waste biomass of several types such as municipal biosolids, municipal solid wastes, and certain industrial and commercial wastes that must be disposed of at additional cost by environmentally acceptable methods. These biomass feedstocks will be discussed in the next chapter, but suffice it to say at this point that many generators of waste biomass will pay a service company for removing and disposing of the wastes, and many of the generators will undertake the task on their own. These kinds of feedstocks often provide an additional economic benefit and revenue stream that can support commercial use of biomass energy.

Another factor is the potential economic benefit that may be realized from the utilization of both waste and virgin biomass as energy resources due to current and future environmental regulations. If carbon taxes are ever imposed on the use of fossil fuels in the United States as they have been in a few other countries to help reduce undesirable automobile and power plant emissions to the atmosphere, additional economic incentives will be available to stimulate development of new biomass energy systems. Certain tax credits and subsidies are already available for commercial use of specific types of biomass energy systems (Klass, 1995).

C. LOCAL AND REGIONAL ECONOMIC EFFECTS OF BIOMASS ENERGY

In addition to the costs of biomass energy, another and probably more important factor should be considered when assessing market prices for biomass energy and biofuels. It is the accumulated, tangible socioeconomic benefits of the commercial utilization of a local or regional energy resource for the local or regional economy. A detailed assessment of these benefits is perhaps best illustrated by the results of a projection done for the state of Wisconsin on the impacts of a 75% increase in Wisconsin's biomass energy use by the year 2010 (Clemmer and Wichert, 1994). The study was referred to briefly in Chapter 2; more detail is presented here. Using indigenous biomass feedstocks, the projection consists of the impacts of 775 MW of new generating capacity and 379 million liters per year of new fuel ethanol production. This amount of biomass energy could supply electricity to 500,000 Wisconsin homes and 10 vol % ethanol–90 vol % gasoline blends (gasohol) to 45% of Wisconsin's automobiles. Investment under this projection generates about three times more jobs, earnings, and output (sales) in Wisconsin than the same level of imported fossil fuel usage and investment. This incremental increase in biomass energy alone is equivalent to 63,234 more job-years of net employment, $1.2 billion in higher wages, and $4.6 billion in additional output. Over the operating life of the technologies analyzed, about $2 billion in avoided payments for imported coal, natural gas, and petroleum fuels could remain in Wisconsin to pay for state-supplied renewable resources, technologies, and labor. Collecting and distributing the wood, corn, and waste feedstocks correspond to 47% of the total net new employment for this industry and create permanent forestry, agriculture, and transportation jobs in Wisconsin's rural communities. Operating and maintaining biomass energy technologies produce 27% of the net employment growth, and installing and manufacturing these technologies generate 13% of the new jobs on a temporary basis. Net savings in consumer income, with environmental regulations, account for the remaining 13% of new jobs. Five of the 11 biomass technologies analyzed for power production are less expensive to operate than a new baseload coal plant, without considering incentives for environmental costs. When federal incentives and potential environmental regulation costs are included, 9 of the 11 biomass technologies cost less than a new coal-fired plant. Ethanol produced by established technologies competes with gasoline at the federal incentive levels in place in the 1990s. Investing in biomass energy instead of fossil fuels in Wisconsin could save the state's residents about $700 million in avoided environmental regulations to control CO_2 and SO_2 emissions from fossil fuels and $250 million in personal income. So it is evident there is more to development of a biomass energy industry that can compete with conventional fossil fuels than the basic costs of biomass energy.

VI. RESEARCH ON VIRGIN BIOMASS PRODUCTION

A large variety of virgin biomass feedstock developments for the production of energy, biofuels, and chemicals is in the research stage in Canada, the

United States, and many other countries. Research is progressing to develop and select special species and clones of trees and herbaceous crops and to develop advanced growth and management procedures for dedicated energy crops. This work is being done in the laboratory and in the field and is aimed at reducing the cost of biomass and increasing the efficiency of production. Research on short-rotation tree growth methods and the screening of woody and herbaceous biomass continues, generally on small-scale test plots. The North American effort has focused on hybrid poplar, willow, switchgrass, and a few other species. The emphasis in South America is on species such as *Eucalyptus* that grow well in semitropical and tropical climates. Larger scale field trials in which dedicated biomass production is integrated with conversion are beginning to evolve in the United States from the research done with small systems. But most of the continuing research in the United States on the selection of suitable biomass is limited to laboratory studies and small-scale test plots. Many of the research programs on feedstock development were started in the 1970s and early 1980s. Based on the research data accumulated in this work, some of the herbaceous and woody biomass species that appear to be good models for energy feedstock production are shown by region in Fig. 4. 9 for the continental United States and Hawaii (Wright, 1994).

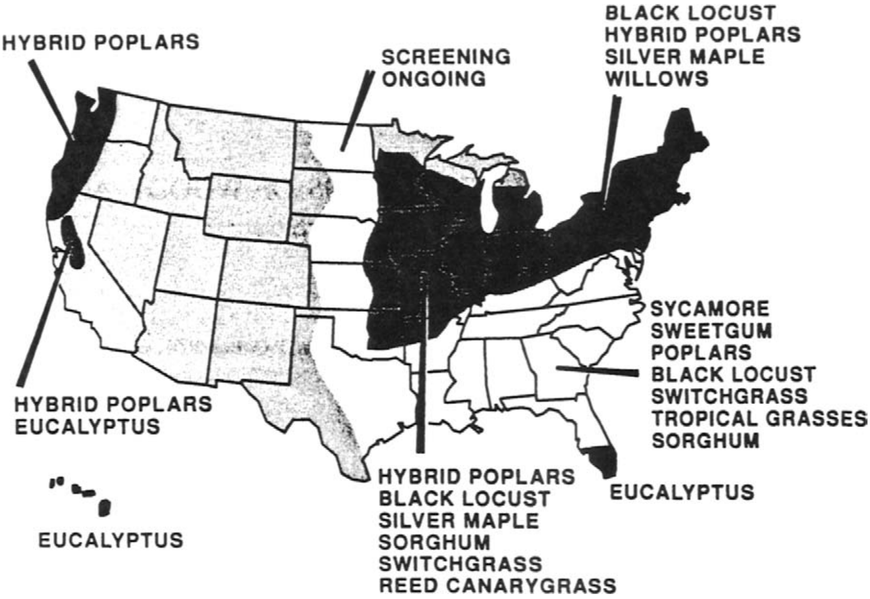

FIGURE 4.9 Woody and herbaceous biomass species recommended for energy feedstock production. From Wright (1994).

A. HERBACEOUS BIOMASS

Considerable research has been conducted to screen and select herbaceous plants as potential biomass candidates that are mainly unexplored in the Continental United States. Other research has concentrated on cash crops such as sugarcane and sweet sorghum, and still other research has emphasized tropical grasses. In the late 1970s, a comprehensive screening study of plants grown in the United States generated a list of 280 promising candidates from which up to 20 species were recommended for field experiments in each region of the country (Saterson and Luppold, 1979). The four highest-yielding species recommended for further tests in each region are listed in Table 4.16. Since many of the plants in the original list of 280 species had not been grown for commercial use, the production costs were estimated as shown in Table 4.17 for the various classes of herbaceous species. The results were used in conjunction with yield and other data to develop the recommendations in Table 4.16.

A large number of research projects directed to small-scale field tests of potential herbaceous energy crops have since been carried out. The productivity ranges for some of the promising species for the U.S. Midwest and Southeast are shown in Table 4.11. The results of this research helped to establish a strategy that herbaceous biomass energy crops should be primarily grasses and legumes produced by use of management systems similar to those used for conventional forage crops. It was concluded that the ideal selection of herbaceous energy crops for these areas would consist of at least one annual species, one warm-season perennial species, one cool-season perennial species, and one legume. Production rates, cost estimates, and environmental considerations indicate that perennial species are preferred to annual species on many sites, but annuals may be more important in crop rotations.

In greenhouse, small-plot, and field-scale research tests conducted to screen tropical grasses as energy crops, three categories emerged, based on the time required to maximize dry-matter yields: short-rotation species (2 to 3 months), intermediate-rotation species (4 to 6 months), and long-rotation species (12 to 18 months) (Alexander, 1991). A sorghum-sudan grass hybrid (Sordan 70A), the forage grass napier grass, and sugarcane were outstanding candidates in these categories. Minimum-tillage grasses that produced moderate yields with little attention were wild *Saccharum* clones and Johnson grass in a fourth category. The maximum yield observed was 61.6 dry t/ha-year for sugarcane propagated at narrow row centers over 12 months. The estimated maximum yield is of the order of 112 dry t/ha-year using new generations of sugarcane and the propagation of ratoon (regrowth) plants for several years after a given crop is planted.

Overall, the research that has been completed in the United States on the development of herbaceous biomass energy crops shows that a wide range of suitable species exist from which good candidates can be chosen for each area.

TABLE 4.16 Reported Maximum Productivities in United States for Recommended Herbaceous Plants[a]

Region[b]	Species	Yield (dry t/ha-year)
Southeastern prairie delta and coast	Kenaf	29.1
	Napier grass	28.5
	Bermuda grass	26.9
	Forage sorghum	26.9
General farm and North Atlantic	Kenaf	18.6
	Sorghum hybrid	18.4
	Bermuda grass	15.9
	Smooth bromegrass	13.9
Central	Forage sorghum	25.6
	Hybrid sorghum	19.1
	Reed canary grass	17.0
	Tall fescue	15.7
Lake states and Northeast	Jerusalem artichoke	32.1
	Sunflower	20.0
	Reed canary grass	13.7
	Common milkweed	12.3
Central and southwestern plains and plateaus	Kenaf	33.0
	Colorado River hemp	25.1
	Switchgrass	22.4
	Sunn hemp	21.3
Northern and western Great Plains	Jerusalem artichoke	32.1
	Sunchoke	28.5
	Sunflower	19.7
	Milkvetch	16.1
Western range	Alfalfa	17.9
	Blue panic grass	17.9
	Cane bluestem	10.8
	Buffalo gourd	10.1
Northwest/Rocky Mountain	Milkvetch	12.1
	Kochia	11.0
	Russian thistle	10.1
	Alfalfa	8.1
California subtropical	Sudan grass	35.9
	Sudan–sorghum hybrid	31.6
	Forage sorghum	28.9
	Alfalfa	19.1

[a] Satterson and Luppold (1979).
[b] As defined by U.S. Dept. of Agriculture (1972); excludes Alaska and Hawaii.

TABLE 4.17 Production Costs for Annual Herbaceous Biomass[a]

Plant group	Model crop used	Whole plant yield (dry t/ha-year)	Cost ($/t)
Tall grasses	Corn	17.3	19.1
Short grasses	Wheat	9.9	17.2
Tall broadleaves	Sunflower	15.0	12.7
Short broadleaves	Sugar beet	13.9	77.1
Legumes	Alfalfa[b]	13.7	20.9
Tubers	Potatoes	9.2	136

[a] Saterson and Luppold (1979).
[b] Perennial.

B. SHORT-ROTATION WOODY CROPS

Research to develop trees as energy crops in the United States via short-rotation intensive culture made significant progress in the 1980s and 1990s. Projections indicate that yields of organic matter can be substantially increased by coppicing techniques and genetic improvements. Advanced designs of whole-tree harvesters, logging residue collection and chipping units, and automated planters for rapid planting have been developed to the point where prototype units have been evaluated in the field and some are being manufactured for commercial use. It is expected that several additional devices will be offered for commercial use. The on going research is also leading to significant changes in forestry harvesting techniques. Clear-cutting is being phased out and partial harvesting or thinning operations are being phased in. New thinning technologies have been proposed for testing in the forests of the Northwest after successful tests in California. The California research data show that the thinning of overgrown stands reduces tree mortality, provides healthier stands, and may offer biomass fuels at a cost that make it possible to operate wood-fueled power plants on a stand-alone basis at a profit in competition with market prices for electric power.

Some of the tree species that have been targeted for continuing research are red alder, black cottonwood, Douglas fir, and ponderosa pine in the Northwest; *Eucalyptus*, mesquite, Chinese tallow, and the leucaena in the West and Southwest; sycamore, Eastern cottonwood, black locust, catalpa, sugar maple, poplar, and conifers in the Midwest; sycamore, sweetgum, European black alder, and loblolly pine in the Southwest; and sycamore, poplar, willow, and sugar maple in the East. Generally, tree growth in research plots is studied in terms of soil type and the requirements for site preparation, planting density, irrigation, fertilization, weed control, disease control, and nutrients. Harvesting methods are equally important, especially in the case of coppice growth for SRWC hardwoods. Although three species native to the region are usually included in the experimental designs, nonnative and hybrid species have often been tested in research plots as well. Advanced biochemical methods and techniques such as tissue culture propagation, genetic transformation, and somaclonal variation are being used in this research to clonally propagate individual genotypes and to regenerate genetically modified species.

After an intensive research effort over about 10 years, SRWC yields in the United States, based on accumulated data are projected to be 9, 9, 11, 17, and 17 dry t/ha-year in the Northeast, South/Southeast, Midwest/Lake, Northwest, and Subtropics, respectively (Wright, 1992). The corresponding research goals are 15, 18, 20, 30, and 30 dry t/ha-year. Hybrid poplar, which grows in many parts of the United States, and *Eucalyptus*, which is limited to Hawaii, Florida, southern Texas, and part of California, have shown the greatest potential thus far for attaining exceptionally fast growth rates. Both have achieved yields in the range of 20 to 43 t/ha-year in experimental trials with selected clones. Continuing research indicates that other promising species are black locust, sycamore, sweetgum, and silver maple.

Research on hybridizing techniques seem to be leading to super trees that have short growth cycles and that yield larger quantities of biomass. Fast-growing clones are being developed for energy farms in which the trees are ready for harvest in as little as 10 years and yield up to 30 m^3/ha-year. Genetic and environmental manipulation has also led to valuable techniques for the fast growth of saplings in artificial light and with controlled atmospheres, humidity, and nutrition. The growth of infant trees in a few months is equivalent to what can be obtained in several years by conventional techniques.

Chemical injections into pine trees have been found to have stimulatory effects on the natural production of resins and terpenes and may result in high yields of these valuable chemicals. Combined oleoresin-timber production in mixed stands of pine and timber trees is under development, and it appears that when short-rotation forestry is used, the yields of energy products and timber can be substantially higher than the yields from separate operations.

One of the largest research projects on SRWC in the Western World, LEBEN or the Large European Bioenergy Project, was reported to be scheduled for initiation in the Abruzzo region of Italy in the mid-1980s and to be established near the end of that decade (Grassi, 1987; Klass, 1987). This project integrates SRWC production, the production of herbaceous energy crops and residues, and biomass conversion to biofuels and energy. About 400,000 t/year of biomass, consisting of 260,000 t/year of woody biomass from 700 ha and 120,000 t/year of agricultural residues from 700 ha of vineyards and olive and fruit orchards, will be used. Later, 110,000 t/year of energy crops from 1050 ha will be utilized. The energy products include liquid fuels (biomassderived oil), charcoal, 200 million kWh/year of electric power, and waste heat for injection into the regional agroforestry and industrial sectors. This project is still in the start-up stages in the mid-1990s.

One of the largest demonstration programs in the United States was started in 1993 in Minnesota where hybrid poplar is grown under short-rotation conditions on a few sites that total 2000 ha. As the results of this program are reported, a much more rigorous analysis of the potential of SWRC for energy will be possible. The ultimate approach to perfecting this technology, however, is to integrate large-scale biomass production with conversion. Little research of this type has been done. The assumptions and projections that have been made to evaluate the technology are based primarily on small-scale laboratory results, what others have reported as research results, or predictions about individual steps that make up the overall system. But this situation is starting to change as government-industry support of integrated biomass production and conversion research make it possible to examine the sustainability of these systems in detail. In the United States, several research projects in which virgin biomass production is integrated with conversion have been selected for field demonstration in plots that are expected to be a minimum of 405 ha (1000 ac) in size (Klass, 1996). This research will provide first-hand experience in operating integrated systems on a sustained basis in which a dedicated biomass feedstock is supplied to a conversion plant. The first group of biomass energy technologies to be scaled up consist of alfalfa production integrated with a gasifier-combined-cycle power plant in Minnesota, switchgrass production integrated with a power plant in Iowa in which biomass and coal are co-fired, hybrid willow production integrated with a power plant in New York in which biomass and coal are co-fired, and an innovative whole tree production system integrated with a power plant in Minnesota (Spaeth and Pierce, 1996). As these projects are implemented, others are expected to be added to the program.

C. AQUATIC BIOMASS

Aquatic biomass, particularly micro- and macroalgae, is more efficient at converting incident solar radiation to chemical energy than most other biomass species. For this reason and the fact that most aquatic plants do not have commercial markets, research was performed in the United States in the late 1970s up to the 1990s to evaluate several species as energy crops. The overall goals of the research were generally directed either to biomass production, often with simultaneous waste treatment, for subsequent conversion to fuels by fermentation, or to species that contain valuable products. The aquatics that have been studied and their main applications are microalgae for liquid fuels, the macrophyte water hyacinth for wastewater treatment and conversion to methane, and marine macroalgae for specialty chemicals and conversion to methane.

Research in the United States on microalgae has focused on the growth of these organisms under conditions that promote lipid formation. This eliminates the high cost of cell harvest because the lipids can sometimes be separated by simple flotation or extraction. The research program supported by the U.S. Department of Energy on microalgae in the 1980s was one of the largest of its kind. It consisted of several projects and emphasized the isolation and characterization of the organisms and the development of microalgae that afford high oil yields. The research included projects on siting studies; collection, screening, and characterization of microalgae; the growth of certain species in laboratory and small-scale production systems; exploration of innovative approaches to microalgae production; and innovative methods for increasing oil formation. Some microalgae, such as *Botryococcus braunii,* have been reported to produce lipid yields that are 40-50% of the dry cell weight under nitrogen-limited conditions (*cf.* Klass, 1985). However, in other research, *B. braunii* has been reported to yield 20-52% of the dry cell weight as liquid hydrocarbons (*cf.* Klass, 1987).

Much of the research on aquatic biomass species as energy resources in the United States has since been terminated or reduced in scope, but it continues in other countries with emphasis on the production of high value products rather than energy.

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