Sustainable Energy

Lecture 10: Biomass Energy

What is Biomass?

- Biomass is all living plant matter as well as organic wastes derived from plants, humans, marine life, and animals.
- Biomass includes trees, grasses, animal dung, as well as sewage, garbage, wood construction residues, and other solid waste stream components.
- Biomass was the primary energy source for human cultures until relatively recent times in the industrial revolution.
- Biomass was still the most important source of energy in the US during the 19th century but was overtaken by 1885 by coal and by 1915 by oil and gas.
- Many developing nations still depend on biomass to supply their heating/cooking needs.

Biomass continued

- Biomass qualifies as a renewable resource because commercially meaningful quantities are regenerated in time scales that are comparable to or less than the time scales of human use of the resource.

The Chemistry of Biomass Production

- Biomass results from the natural process of the conversion of solar energy to high-energy molecules that can be stored, transported and used conveniently.
- Plants grow and produce biomass by the process of photosynthesis.
- Photosynthesis uses sunlight to convert water and carbon dioxide (fixed by plants) into carbohydrates, oils and other complex organic molecules.
- Conversion efficiencies of plants are about 1-2%.
- The potential impacts/availability of biomass energy depend upon how rapidly biomass can be produced and converted into energy.
- Real limitations exist on the number of acres that can be used to produce biomass fuel.

Photosynthesis/Basic equation

$$6CO_2 + 6H_2O \xrightarrow[\text{catalysts}]{\text{sunlight}} C_6H_{12}O_6 + 6O_2 \quad \Delta G^o = 480\ \text{kJ/mol}$$

Chemical pathways of Photosynthesis

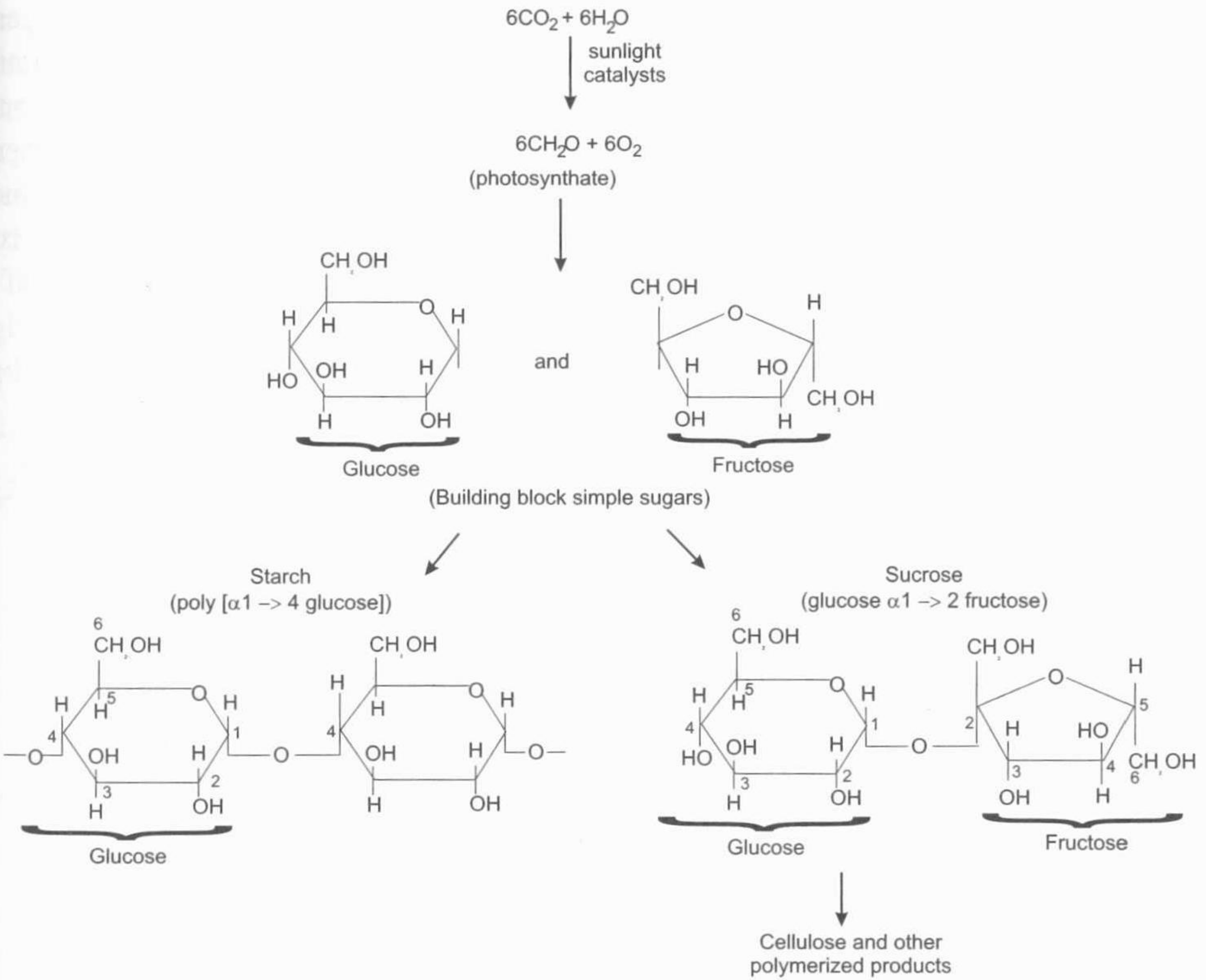


Figure 10.1. Representation of major chemical pathways in the photosynthesis of plants to convert carbon dioxide to carbohydrates and other biomass compounds.

Renewability Indices

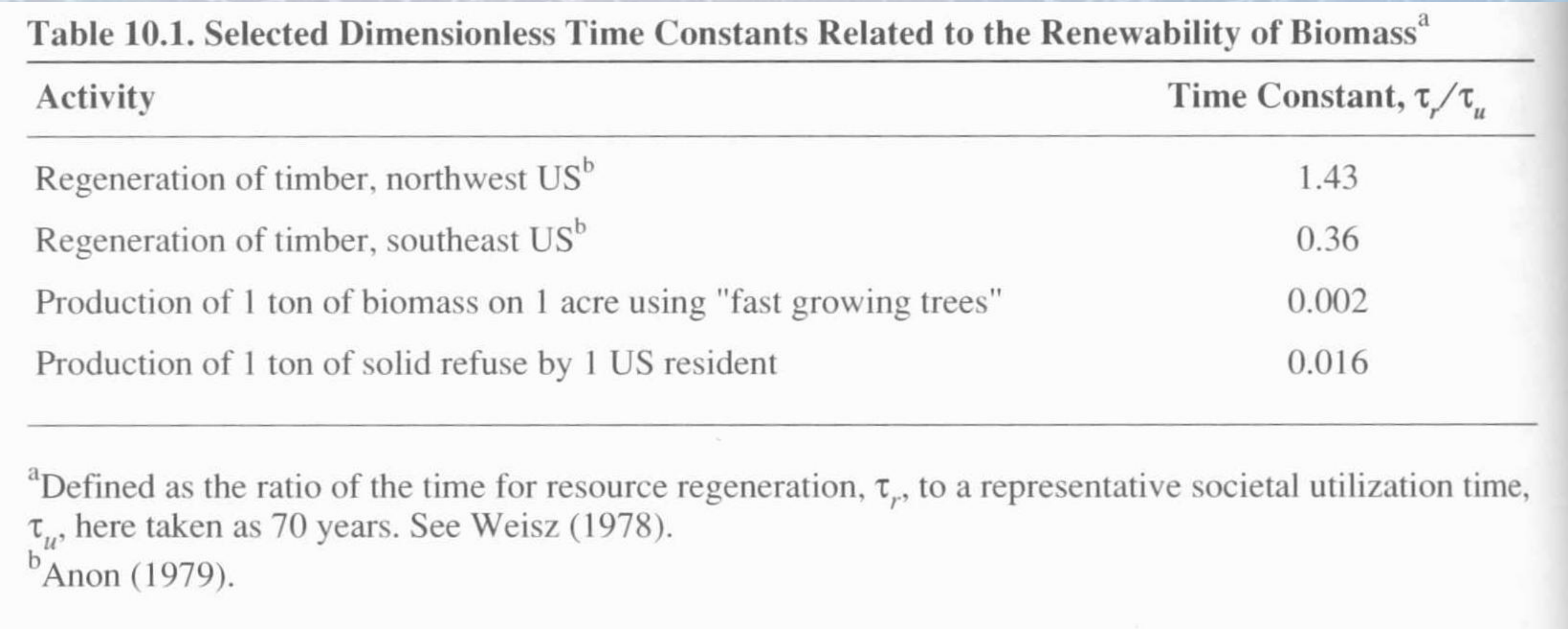


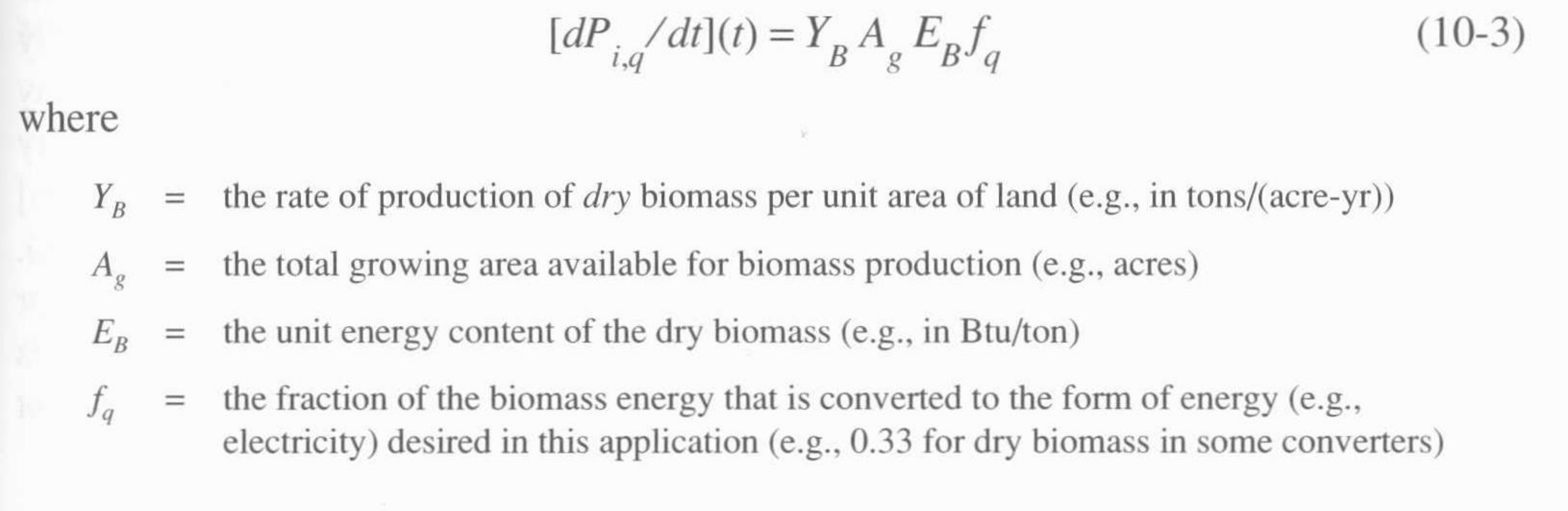
Table 10.1. Selected Dimensionless Time Constants Related to the Renewability of Biomass[a]

Activity	Time Constant, τ_r/τ_u
Regeneration of timber, northwest US[b]	1.43
Regeneration of timber, southeast US[b]	0.36
Production of 1 ton of biomass on 1 acre using "fast growing trees"	0.002
Production of 1 ton of solid refuse by 1 US resident	0.016

[a] Defined as the ratio of the time for resource regeneration, τ_r, to a representative societal utilization time, τ_u, here taken as 70 years. See Weisz (1978).

[b] Anon (1979).

Factors Effecting Production of Rates of Biomass



$$[dP_{i,q}/dt](t) = Y_B A_g E_B f_q \tag{10-3}$$

where

Y_B = the rate of production of *dry* biomass per unit area of land (e.g., in tons/(acre-yr))

A_g = the total growing area available for biomass production (e.g., acres)

E_B = the unit energy content of the dry biomass (e.g., in Btu/ton)

f_q = the fraction of the biomass energy that is converted to the form of energy (e.g., electricity) desired in this application (e.g., 0.33 for dry biomass in some converters)

Factors Effecting Consumption Rates of Biomass

$$[dC_{j,Q}/dt](t) = Y_N A_N E_N f_j f_Q \tag{10-4}$$

where

Y_N = the population density in the area to be serviced by the biomass (people/acre)

A_N = the total area of the region to be serviced (acres)

E_N = the average per capita energy consumption rate in this service area [Btu/(person-yr)]

f_j = the fraction of the total average energy consumption that is made up of energy of the particular type j to be supplied by biomass (e.g., electricity) (typically $f_j \approx 0.33$)

f_Q = the fraction of energy of type j that is to be supplied by biomass (0 to 1.0)

Biomass for Energy Production

- Utilization Options
  - Biomass can be converted into a wide range of useful forms of energy (See Figure 10.2)
- Advantages of biomass
  - Renewable energy source
  - Domestic availability
  - Widely dispersed and can function as a distributed energy source.
  - Many forms of energy can be made from biomass.
  - Biomass-derived products can be substituted for metallic or plastics that require high energy inputs for production.
  - Biomass can provide a way to manage municipal and agricultural wastes.
  - Biomass use can combat the effects of global warming.
  - Biomass produces lower emissions of pollutants (sulfur oxides).
  - Biomass can be mixed with other fuels such as coal.

Biomass for energy…continued

- Disadvantages of biomass
  - The energy density of biomass is low compared to fossil fuels.
  - Raw biomass has a high water content and requires drying to increase it’s energy density.
  - Environmental impacts of intensive crop production are major:
    - Water use
    - Depletion of soil nutrients
    - Soil erosion
    - Nitrate and pesticide pollution
    - Competition for food production acreage
    - Transportation costs can reduce the environmental benefits of biomass.

Biomass Resources

- Total US primary energy consumption in 2003 was 100 Quads; 3% of the total was supplied by biomass.
- World consumption was about 360 Quads.
- In the US the pulp and paper industry is the major contributor.
- The existing commercial biomass power generating industry in the United States, which consists of approximately 1,700 MW (megawatts) of operating capacity actively supplying power to the grid, produces about 0.5 percent of the U.S. electricity supply.
- This level of biomass power generation avoids approximately 11 million tons per year of CO_2 emissions from fossil fuel combustion.
- It also avoids approximately two million tons per year of CH_4 emissions from the biomass residues that, in the absence of energy production, would otherwise be disposed of by burial (in landfills, in disposal piles, or by the plowing under of agricultural residues), by spreading, and by open burning

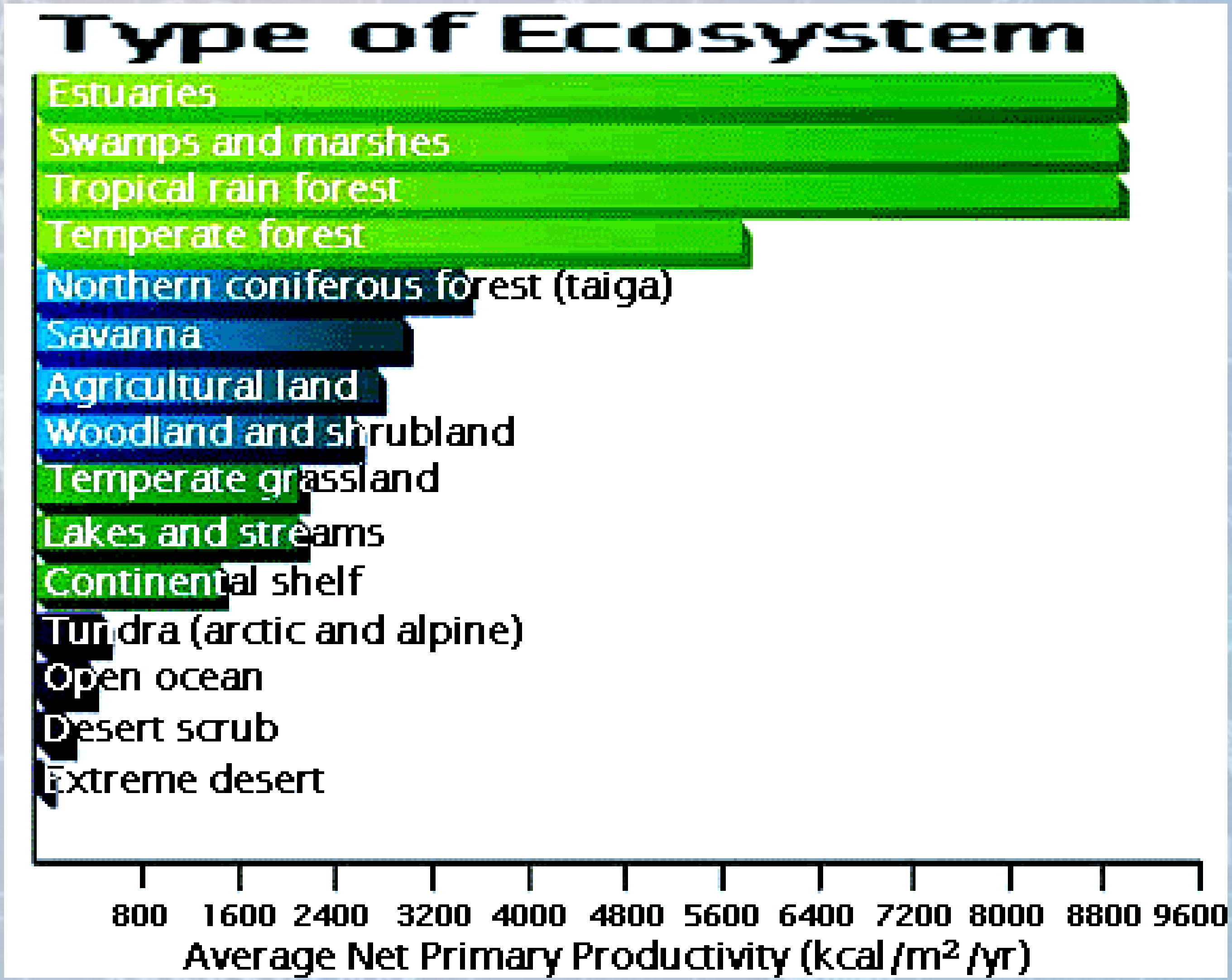
Biodiesel: An Interesting Example

- **Biodiesel production capacity is growing rapidly, with an average annual growth rate from 2002-2006 of over 40%.[**
- **For the year 2006, the latest for which actual production figures could be obtained, total world biodiesel production was about 5-6 million tons, with 4.9 million tons processed in Europe[(of which 2.7 million tons was from Germany) and most of the rest from the USA.[3**
- **The capacity for 2007 in Europe totaled 10.3 million tons. This compares with a total demand for diesel in the US and Europe of approximately 490 million tons (147 billion gallons).[3**
- **Total world production of vegetable oil for all purposes in 2005/06 was about 110 million tons, with about 34 million tons each of palm oil and soybean oil.[3**
- **According to a study written by Drs. Van Dyne and Raymer for the Tennessee Valley Authority, the average US farm consumes fuel at the rate of 82 liters per acre (8.75 US gallons per acre) of land to produce one crop.**
- **However, average crops of rapeseed produce oil at an average rate of 1,029 L/ha (110 US gal/acre), and high-yield rapeseed fields produce about 1,356 L/ha (145 US gal/acre). The ratio of input to output in these cases is roughly 1:12.5 and 1:16.5.**
- **Worldwide production of vegetable oil and animal fat is not yet sufficient to replace liquid fossil fuel use. Furthermore, some object to the vast amount of farming and the resulting fertilization, pesticide use, and land use conversion that would be needed to produce the additional vegetable oil.**
- **The estimated transportation diesel fuel and home heating oil used in the United States is about 160 million tons (350 billion pounds) according to the Energy Information Administration, US DOE.[4**
- **In the United States, estimated production of vegetable oil for all uses is about 11 million tons (24 billion pounds) and estimated production of animal fat is 5.3 million tons (12 billion pounds).[42]**
- **If the entire arable land area of the USA (470 million acres, or 1.9 million square kilometers) were devoted to biodiesel production from soy, this would just about provide the 160 million tons required (assuming an optimistic 98 GPa of biodiesel).**
- **This land area could in principle be reduced significantly using algae, if the obstacles can be overcome. The US DOE estimates that if algae fuel replaced all the petroleum fuel in the United States, it would require 15,000 square miles (38,849 square kilometers), which is a few thousand square miles larger than Maryland, or 1.3 Belgiums, assuming a yield of 15000 GPa.**
- **The advantages of algae are that it can be grown on non-arable land such as deserts or in marine environments, and the potential oil yields are much higher than from plants.**

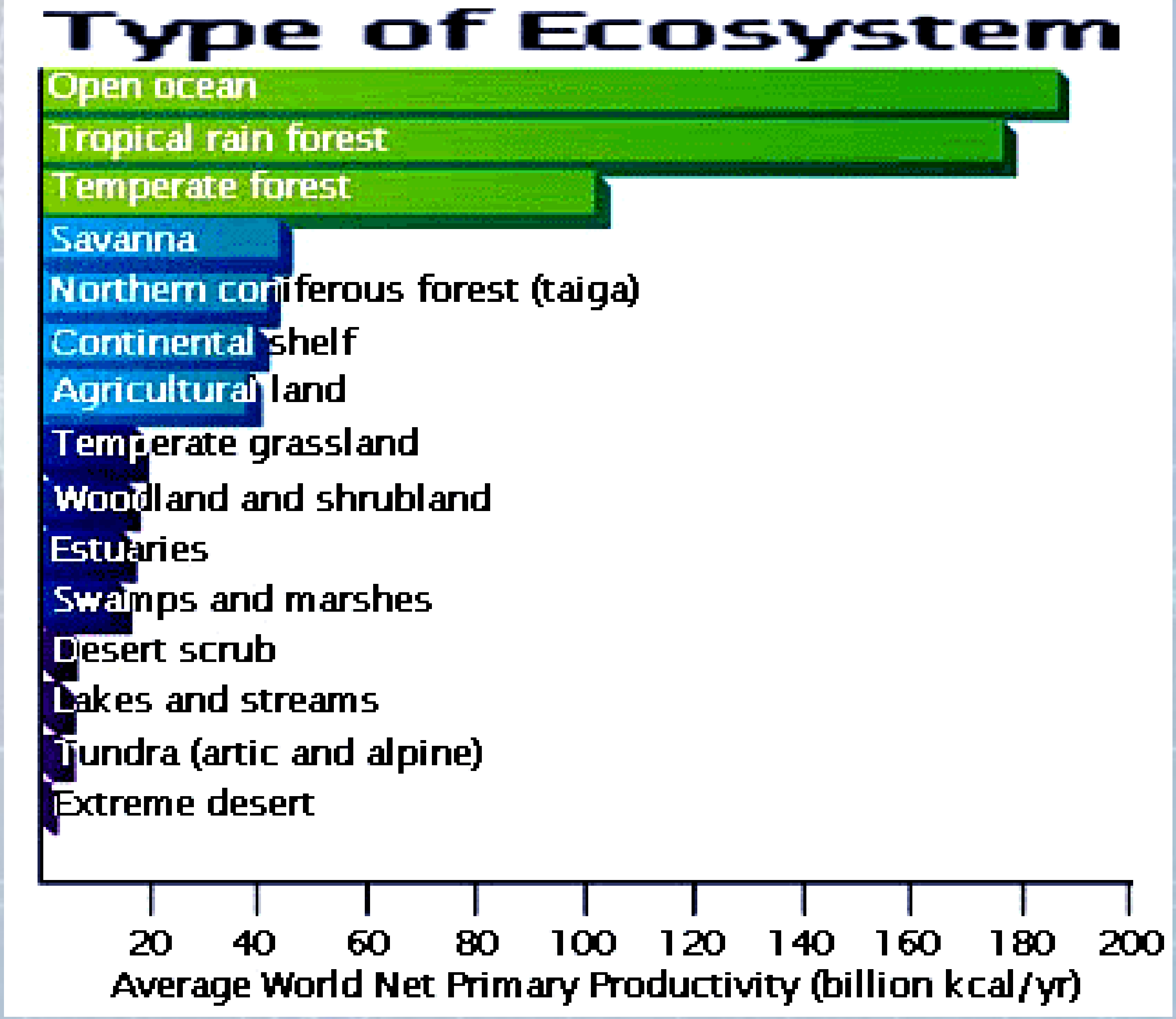
Biodiesel continued

- **Some typical yields in cubic decimeters (liters) of biodiesel per hectare (10,000 square meters):**
  - **Algae: 500-20,000 GPa**
  - **Chinese tallow: 699 GPa**[;4;5]
  - **Hemp: 165 GPa**[47]
  - **Palm oil: 780 - 1490 dm^3 ; 80-160 GPa**[8]
  - **Rapeseed: 100-145 Gap**
  - **Coconut: 353 dm^3; 38 GPa**
  - **Soy: 76-161 dm^3; 8-17 GPa**] **(Soy is used in 80% of USA biodiesel)**
  - **Peanut: 138 dm^3; 15 GPa**
  - **Sunflower: 126 dm^3; 13 GPa**
  - **(Divide by 9.35 to convert liter per hectare to gallons per acre)**
- **Algae grow rapidly and can have a high percentage of lipids, or oils. They can double their mass several times a day and produce at least 15 times more oil per acre than alternatives such as rapeseed, palms, soybeans, or jatropha. Moreover, algae-growing facilities can be built on coastal land unsuitable for conventional agriculture.**
- **The hard part about algae production is growing the algae in a controlled way and harvesting it efficiently.**
- **Most companies pursuing algae as a source of biofuels are pumping nutrient-laden water through plastic tubes (called “bioreactors”) that are exposed to sunlight (and so called photobioreactor or PBR).**
- **Running a PBR is more difficult than a open pond, and more costly.**

Net Primary Productivity by Ecosystem



Total Primary Productivity by Ecosystem



Estimated Biomass for Human Consumption (not total produced)

Type	Mean Biomass	Minimum Replacement Rate
	(kg dryC / m²)	(years)
Tropical rain Forest	45	20.5
Tropical monsoon Forest	35	21.88
Temperate evergreen forest	35	26.52
Temperate deciduous forest	30	25
Boreal forest	20	25
Mediterranean open forest	18	24
Desert and semidesert scrub	0.7	7.78
Extreme desert, rock, sand or ice sheets	0.02	6.67
Cultivated land	1	1.54
Swamp and marsh	15	7.5
Lakes and streams	0.02	0.08
Total continental	12.57	16.23
Open Ocean	0.003	0.02
Upwelling zones	0.02	0.04
Continental shelf	0.01	0.03
Algal beds and reefs	2	0.8
Estuaries & mangroves	1	0.67
Total marine	0.01	0.07
Grand total	3.68	11.02

Figure 10.2

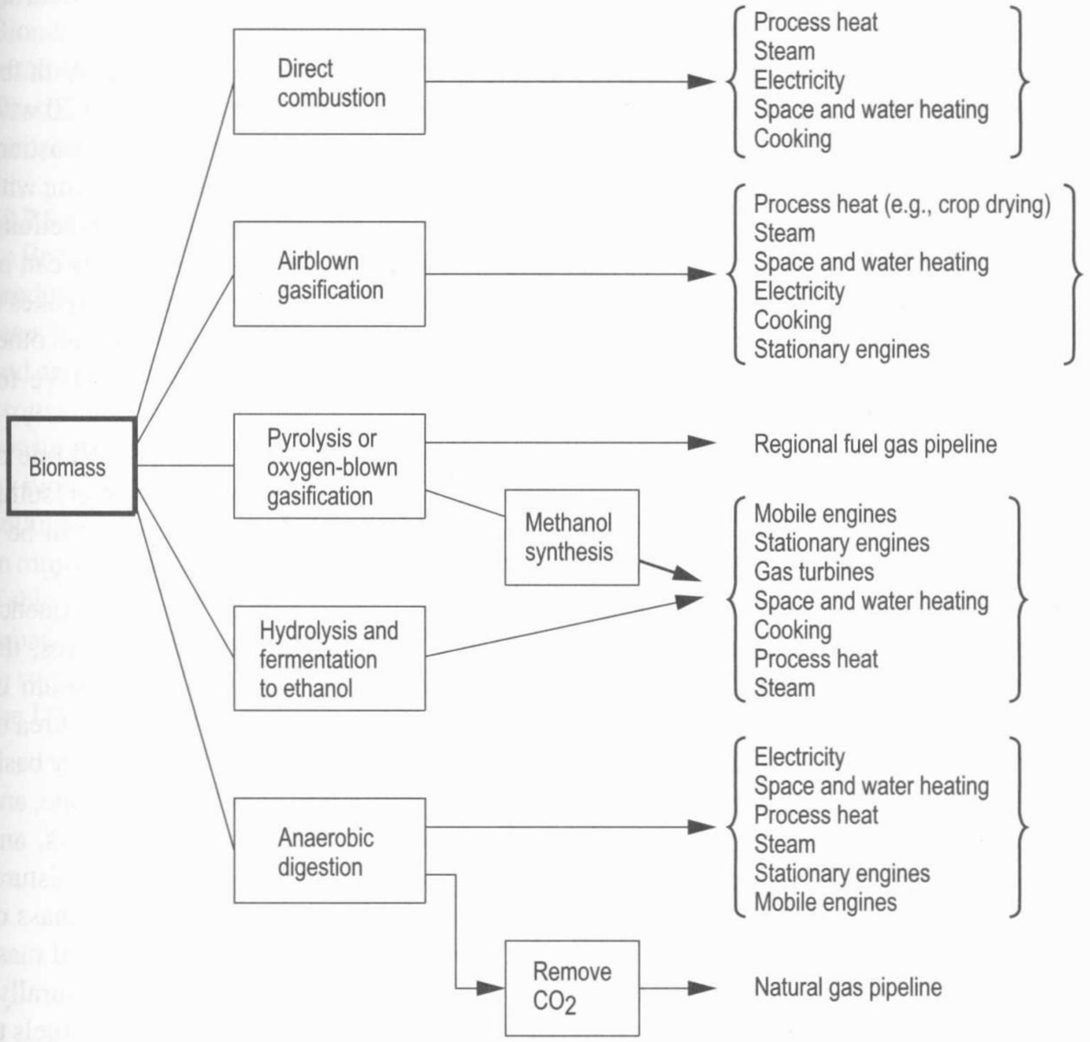


Figure 10.2. Processes for conversion of biomass to fuels, chemicals, and heat from various applications. Source: OTA (1980).

Table 10.2 Biomass Production Rates

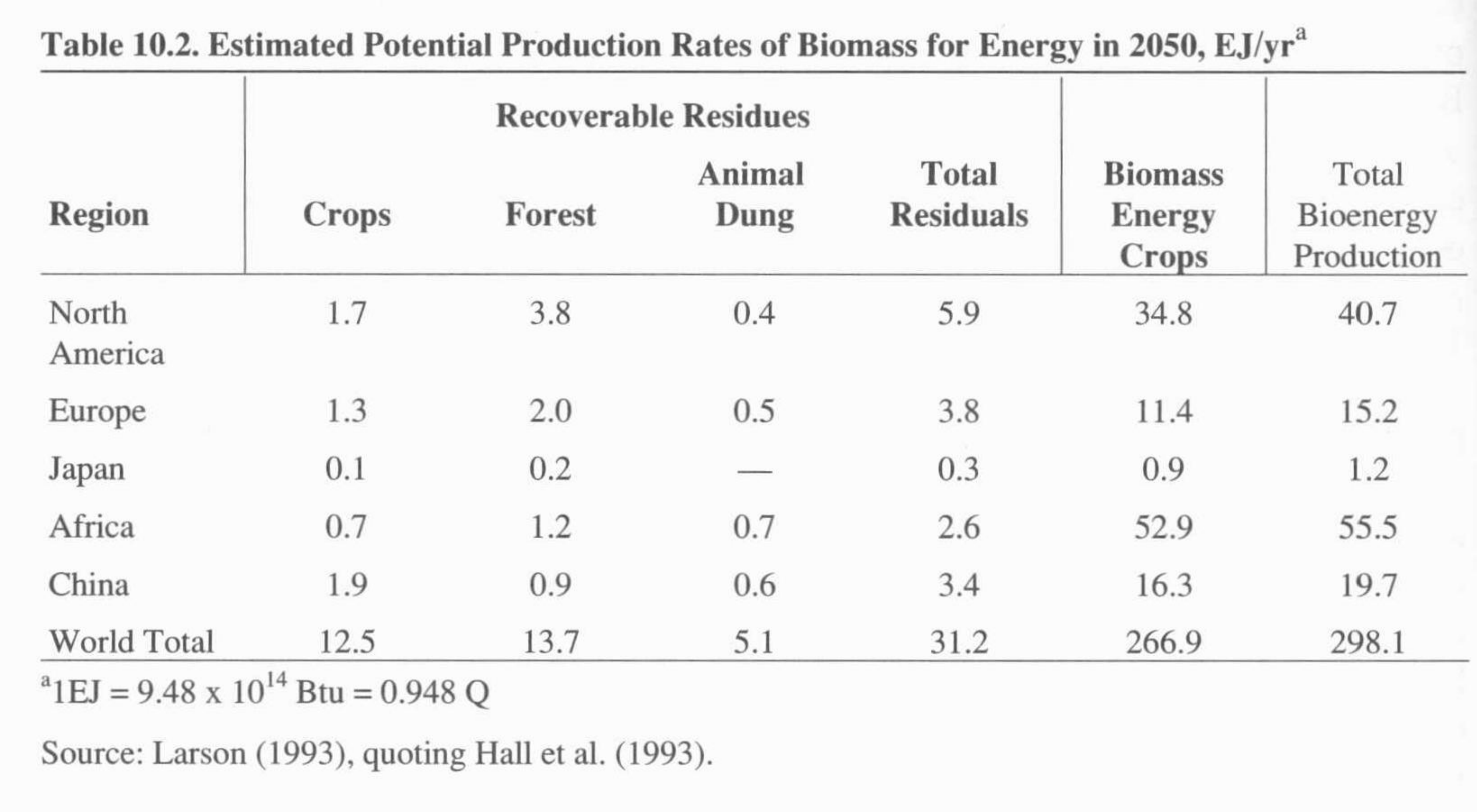


Table 10.2. Estimated Potential Production Rates of Biomass for Energy in 2050, EJ/yr[a]

Region	Recoverable Residues					
	Crops	Forest	Animal Dung	Total Residuals	Biomass Energy Crops	Total Bioenergy Production
North America	1.7	3.8	0.4	5.9	34.8	40.7
Europe	1.3	2.0	0.5	3.8	11.4	15.2
Japan	0.1	0.2	—	0.3	0.9	1.2
Africa	0.7	1.2	0.7	2.6	52.9	55.5
China	1.9	0.9	0.6	3.4	16.3	19.7
World Total	12.5	13.7	5.1	31.2	266.9	298.1

[a] 1EJ = 9.48×10^{14} Btu = 0.948 Q

Source: Larson (1993), quoting Hall et al. (1993).

Residual Biomass in the US

Chemical and Physical Properties

- **Table 10.4 shows typical values for various fuel properties for biomass.**
- **Raw biomass can be up to 75% water.**
- **The inorganic matter content of biomass can be significant (up to 2%).**
- **Table 10.5 provides examples of trace inorganic elements present in biomass.**

Table 10.3

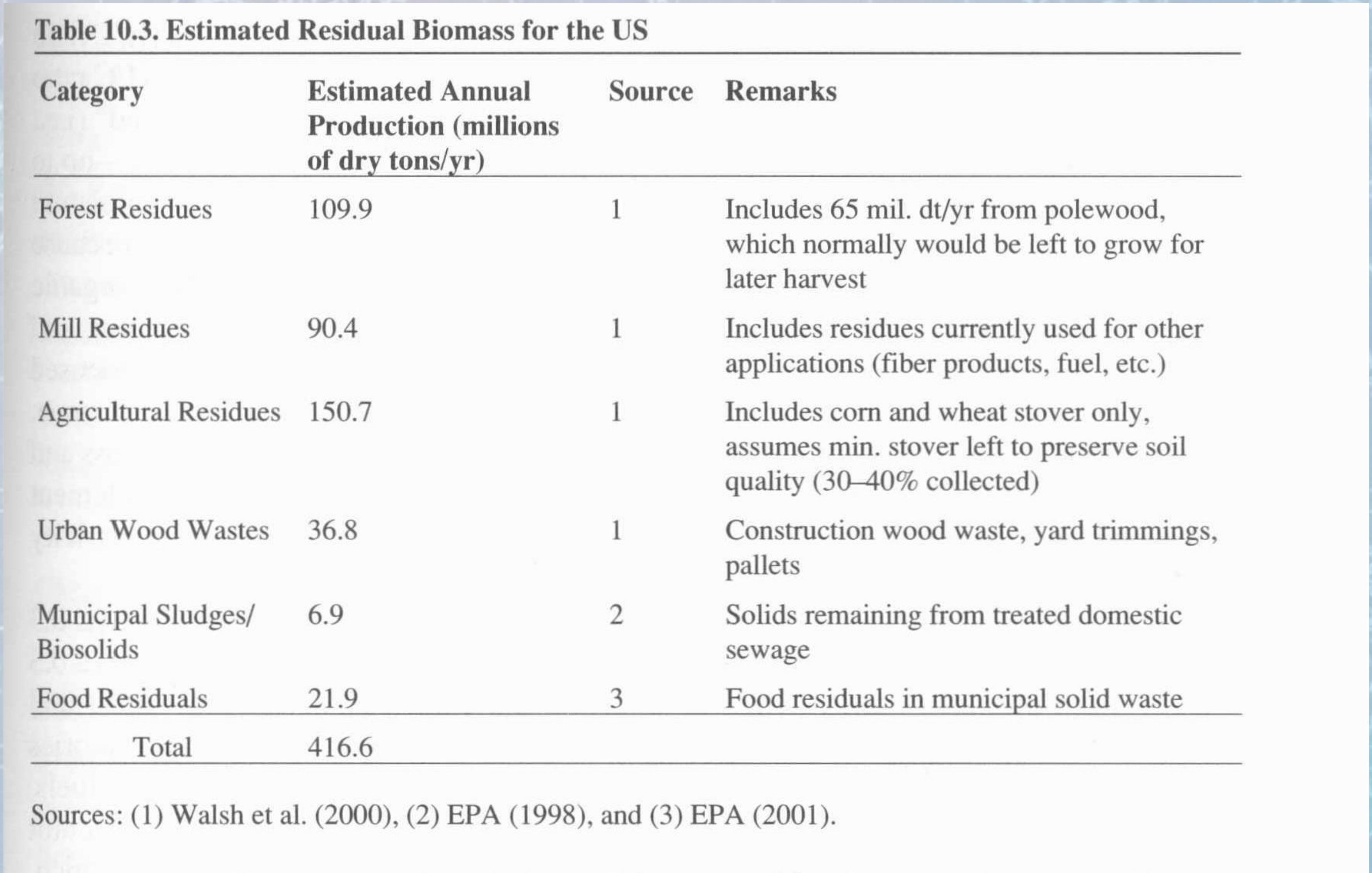


Table 10.3. Estimated Residual Biomass for the US

Category	Estimated Annual Production (millions of dry tons/yr)	Source	Remarks
Forest Residues	109.9	1	Includes 65 mil. dt/yr from polewood, which normally would be left to grow for later harvest
Mill Residues	90.4	1	Includes residues currently used for other applications (fiber products, fuel, etc.)
Agricultural Residues	150.7	1	Includes corn and wheat stover only, assumes min. stover left to preserve soil quality (30–40% collected)
Urban Wood Wastes	36.8	1	Construction wood waste, yard trimmings, pallets
Municipal Sludges/ Biosolids	6.9	2	Solids remaining from treated domestic sewage
Food Residuals	21.9	3	Food residuals in municipal solid waste
Total	416.6		

Sources: (1) Walsh et al. (2000), (2) EPA (1998), and (3) EPA (2001).

Table 10.4

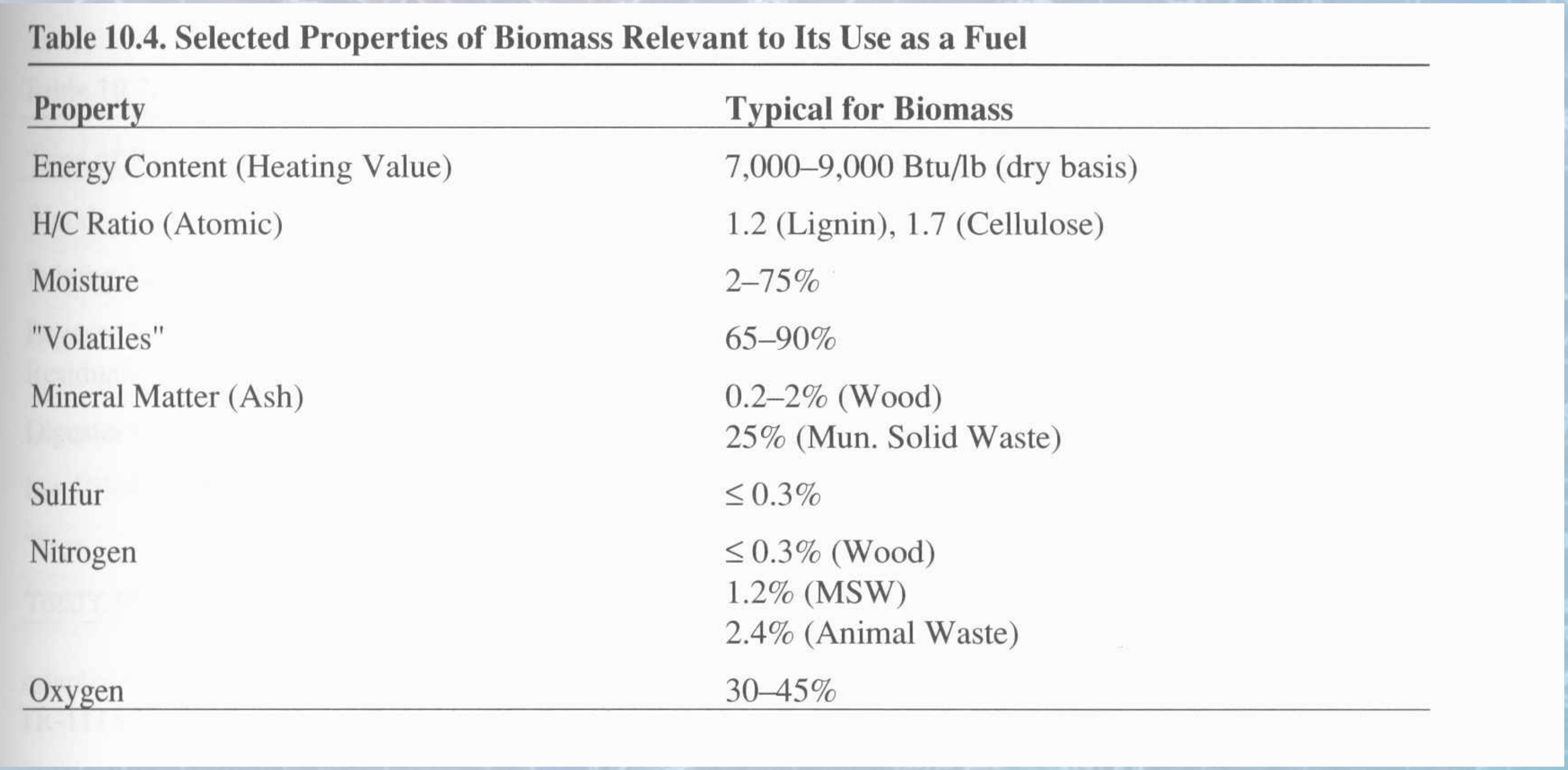


Table 10.4. Selected Properties of Biomass Relevant to Its Use as a Fuel

Property	Typical for Biomass
Energy Content (Heating Value)	7,000–9,000 Btu/lb (dry basis)
H/C Ratio (Atomic)	1.2 (Lignin), 1.7 (Cellulose)
Moisture	2–75%
"Volatiles"	65–90%
Mineral Matter (Ash)	0.2–2% (Wood) 25% (Mun. Solid Waste)
Sulfur	≤ 0.3%
Nitrogen	≤ 0.3% (Wood) 1.2% (MSW) 2.4% (Animal Waste)
Oxygen	30–45%

Table 10.5

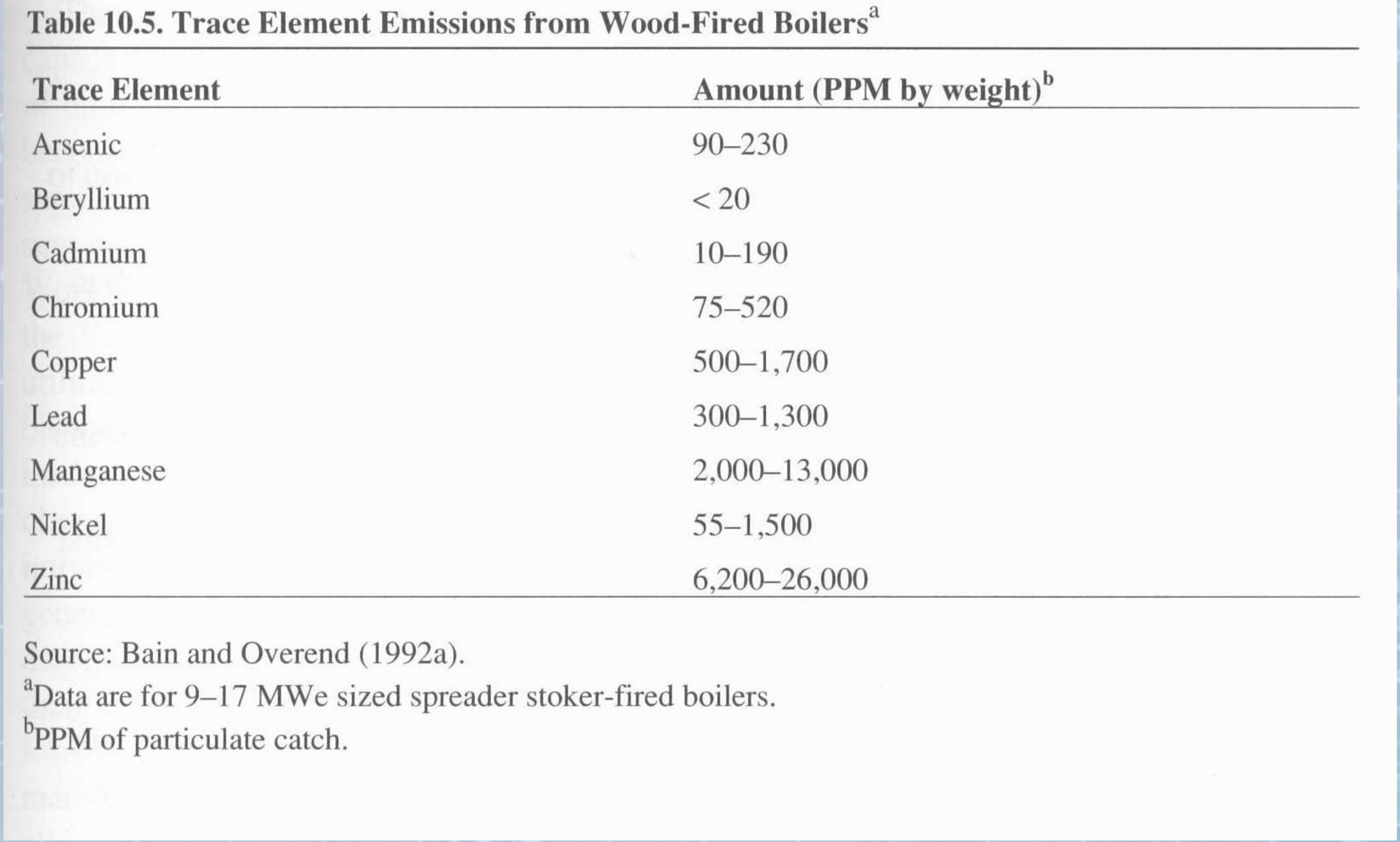


Table 10.5. Trace Element Emissions from Wood-Fired Boilers[a]

Trace Element	Amount (PPM by weight)[b]
Arsenic	90–230
Beryllium	< 20
Cadmium	10–190
Chromium	75–520
Copper	500–1,700
Lead	300–1,300
Manganese	2,000–13,000
Nickel	55–1,500
Zinc	6,200–26,000

Source: Bain and Overend (1992a).

[a] Data are for 9–17 MWe sized spreader stoker-fired boilers.

[b] PPM of particulate catch.

Biomass Production

- Table 10.6 provides some useful numbers on biomass production and utilization.

Table 10.6

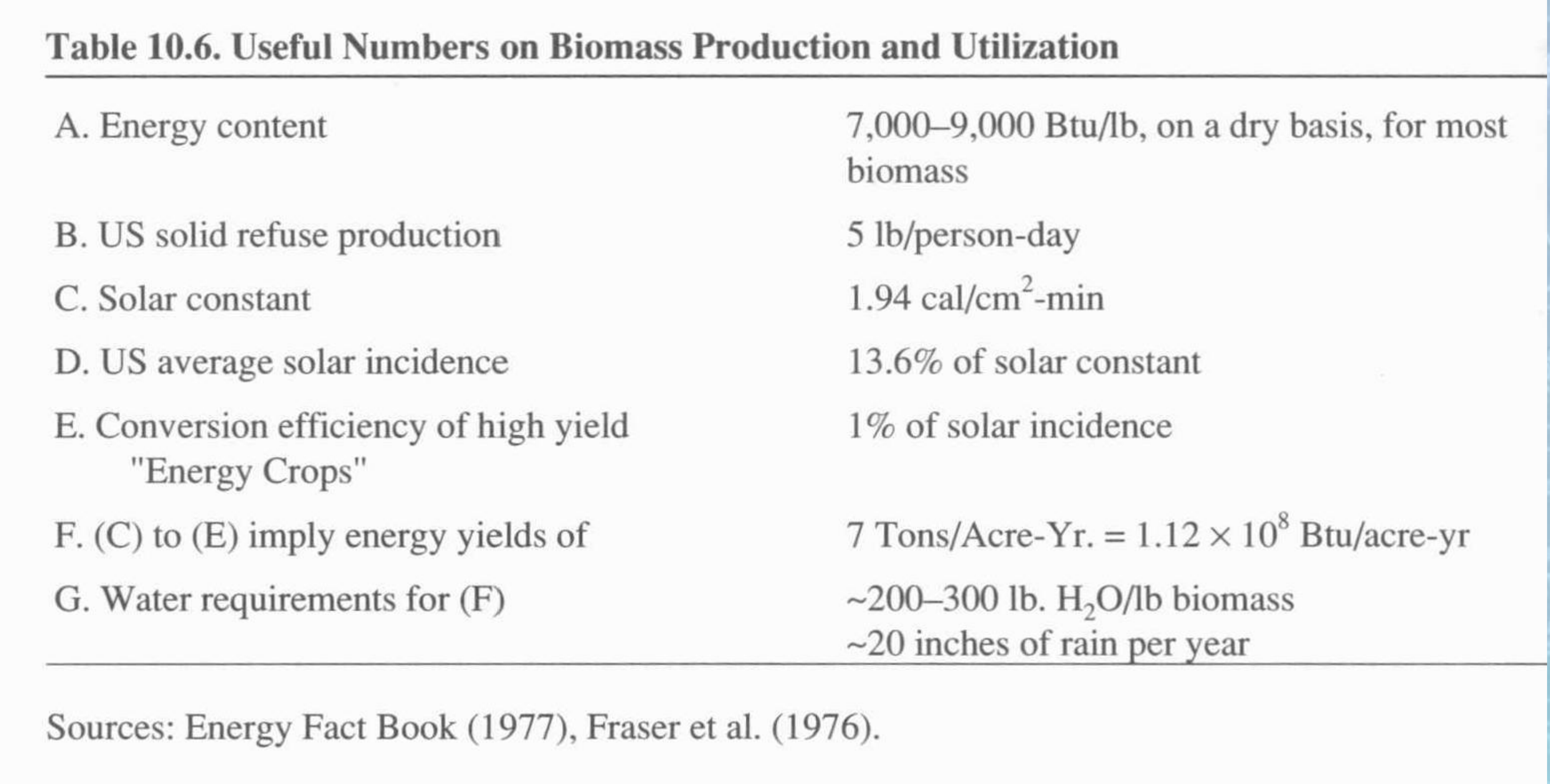


Table 10.6. Useful Numbers on Biomass Production and Utilization

A. Energy content	7,000–9,000 Btu/lb, on a dry basis, for most biomass
B. US solid refuse production	5 lb/person-day
C. Solar constant	1.94 cal/cm^2-min
D. US average solar incidence	13.6% of solar constant
E. Conversion efficiency of high yield "Energy Crops"	1% of solar incidence
F. (C) to (E) imply energy yields of	7 Tons/Acre-Yr. = 1.12×10^8 Btu/acre-yr
G. Water requirements for (F)	~200–300 lb. H_2O/lb biomass ~20 inches of rain per year

Sources: Energy Fact Book (1977), Fraser et al. (1976).

Thermal Conversion of Biomass

- Biomass to electricity
  - Co-firing with coal to reduce sulfur emissions
  - Re-powering (retrofitting existing plants to biomass fuel or adding a biomass-fired generator).
  - Direct combustion in a Rankine cycle plant.
  - Combined cycle plants using gas from biomass gasification
  - Thermal or hydrothermal conversion of biomass to other fuels for combustion (steam generation) or to fuel cells.
- Table 10.7 provides data on current power generation using biomass.

Table 10.7

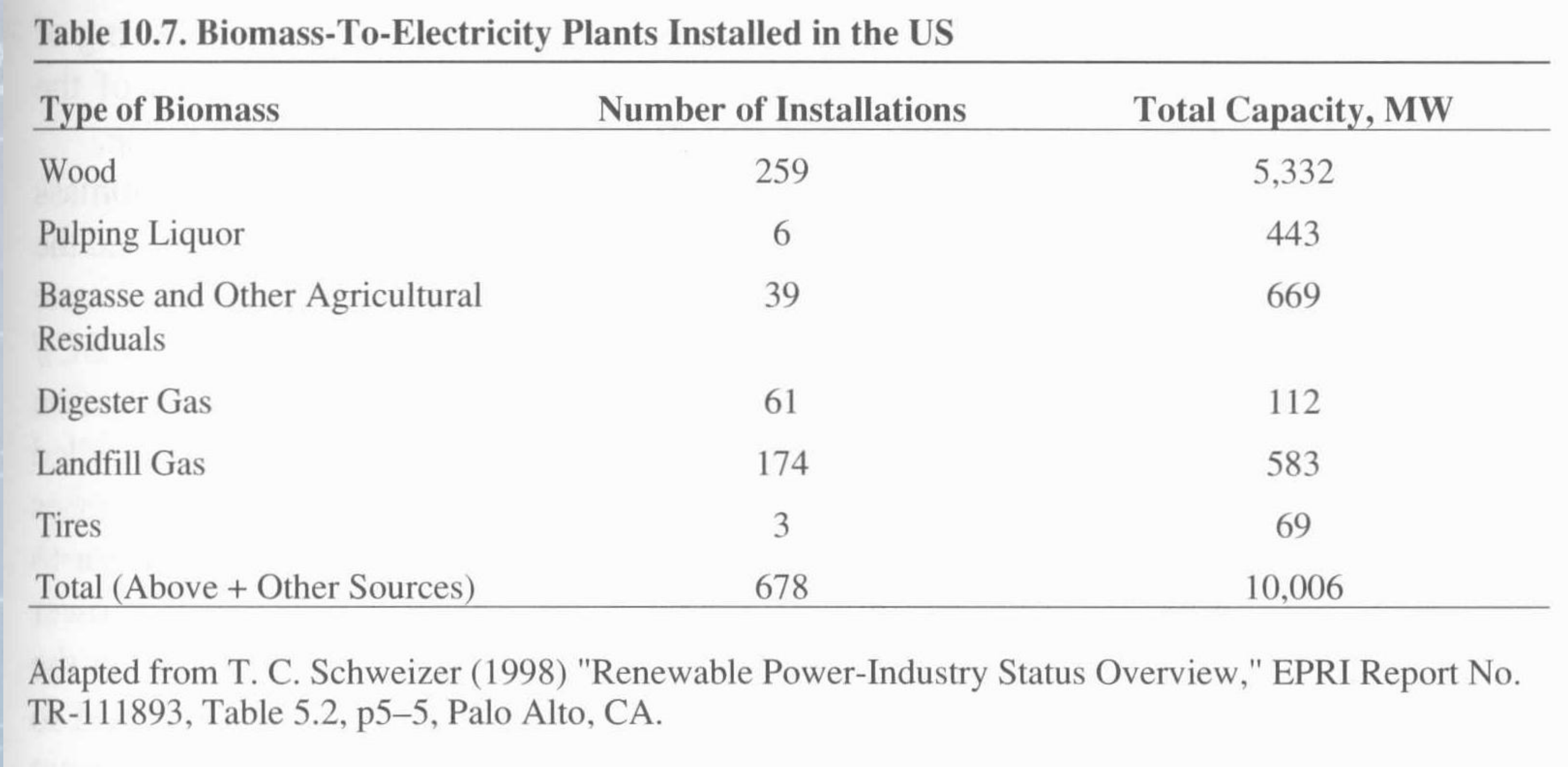


Table 10.7. Biomass-To-Electricity Plants Installed in the US

Type of Biomass	Number of Installations	Total Capacity, MW
Wood	259	5,332
Pulping Liquor	6	443
Bagasse and Other Agricultural Residuals	39	669
Digester Gas	61	112
Landfill Gas	174	583
Tires	3	69
Total (Above + Other Sources)	678	10,006

Adapted from T. C. Schweizer (1998) "Renewable Power-Industry Status Overview," EPRI Report No. TR-111893, Table 5.2, p5–5, Palo Alto, CA.

Biomass to fuel

- Thermal and hydrothermal processes can also be used to convert biomass feedstocks into gaseous and liquid fuels.
  - Pyrolysis – thermal treatment in the absence of oxygen to gasify the biomass to carbon monoxide and hydrogen (syngas).
  - Hydrolysis – food processing wastes with high levels of fats and oils can be easily hydrolyzed to produce low-Btu gas and biodiesel fuel.
  - Gasification
    - Biomass combined cycle (BGCC)
    - Black liquor gasification combined cycle (BLGCC)
    - BGCC and BLGCC plants could generate 8 GWe for the forest products industry.
    - Black liquor is a waste product from making cellulose from wood.
    - Forest residues and residues from pulp and paper making in the Us could fuel 30 GWe by BGCC

Bioconversion

- Bioconversion refers to the direct or adaptive use of the chemistry of living organisms to transform one substance to another.
  - Fermentation – using bacteria, yeast and fungi to produce ethanol from cellulosic biomass.
  - Anaerobic digestion – using bacteria to produce methane.
  - Composting – using bacteria and other decomposers to produce compost and potting soils high in nutrients (nitrogen, phosphorus and organic material).
- Bioconversion processes can be used on raw biomass or industrial/municipal wastes.
- Please see Figures 10.6, 10.7, 10.8, 10.9 and Table 10.8 for details.

Ethanol Production

- David Pimentel, a professor at Cornell University widely known for his research in alternative fuels, favors Fischer-Tropsch diesel (from coal gasification) over ethanol or biodiesel. Both ethanol and biodiesel are derived from agricultural products such as corn or soybeans and blended with conventional fuel before use in cars or trucks. "This is much better than importing oil from foreign countries," Pimentel said. "It is true it takes 2 btu to get 1 btu, but ethanol does the same. It is better than ethanol, whose environmental impacts are 10 times worse than turning coal to liquids."
- Pimentel said corn -- used to make ethanol -- causes more soil erosion and uses more nitrogen fertilizer than other crops. Nitrogen fertilizers are typically produced from natural gas.
- Also, the production of 1 gallon of ethanol requires 1,700 gallons of water and the process generates 12 gallons of waste. The coal-to-liquids technology would have none of these issues, he said.

Figure 10.6

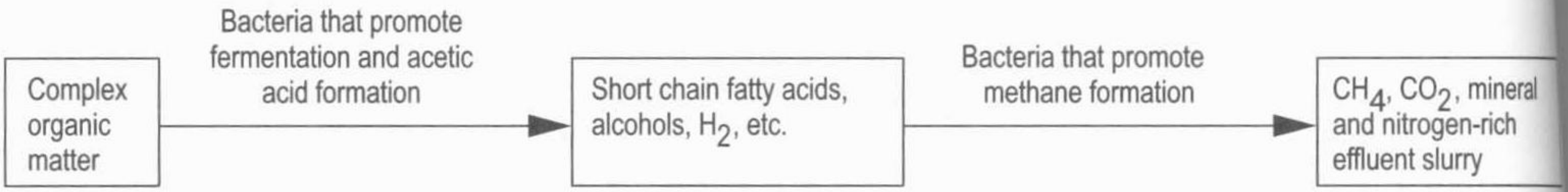


Figure 10.6. Schematic of the overall process chemistry for production of biogas by anaerobic digestion of wet biomass.

Figure 10.8

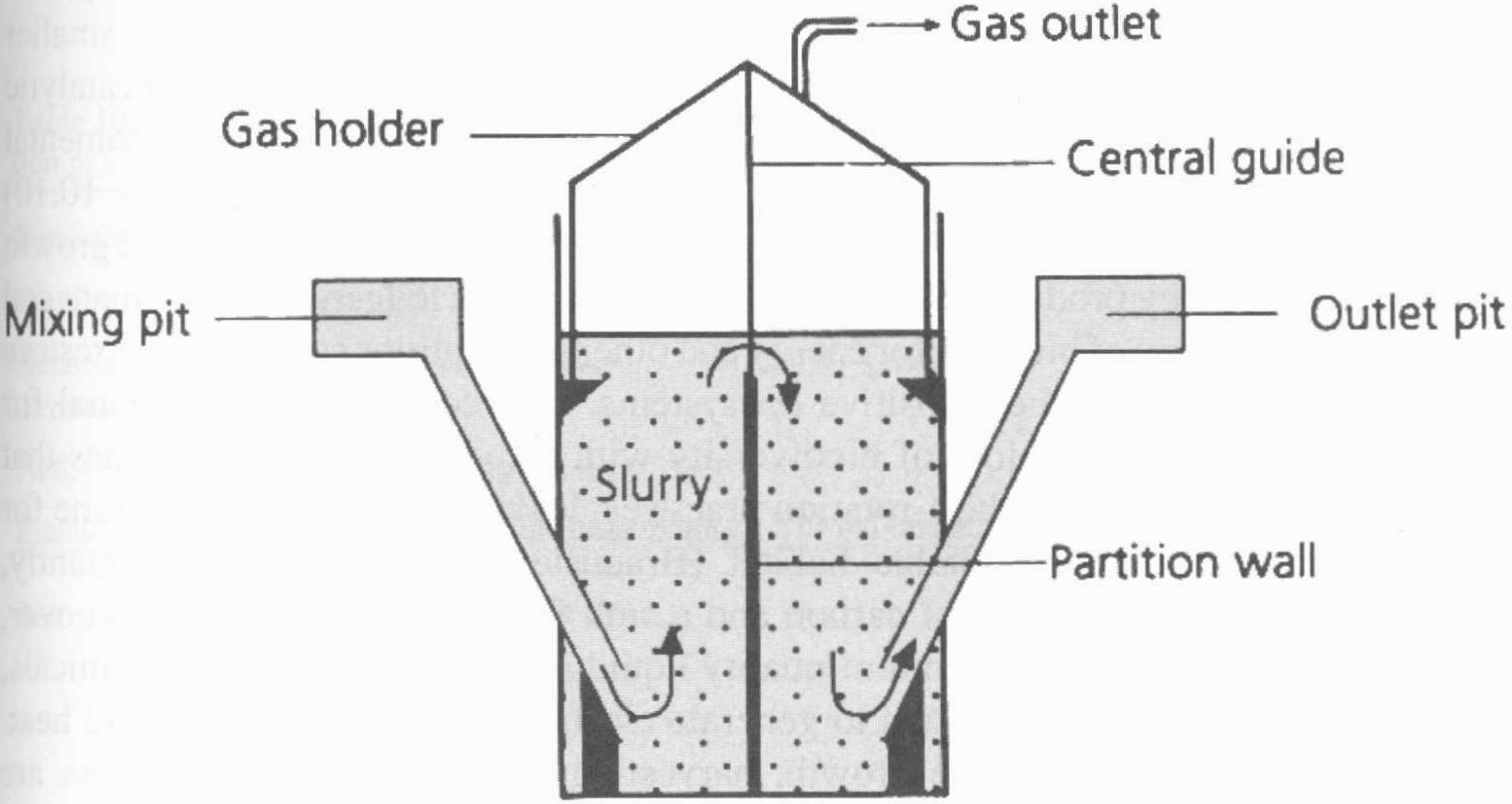


Figure 10.8. Floating cover small scale anaerobic digester for biogas production from wet biomass (widely used in India). Source: Gunnerson and Stuckey (1986). See also Larson (1993). Reprinted with permission of *Annual Review of Energy and the Environment*.

Figure 10.9

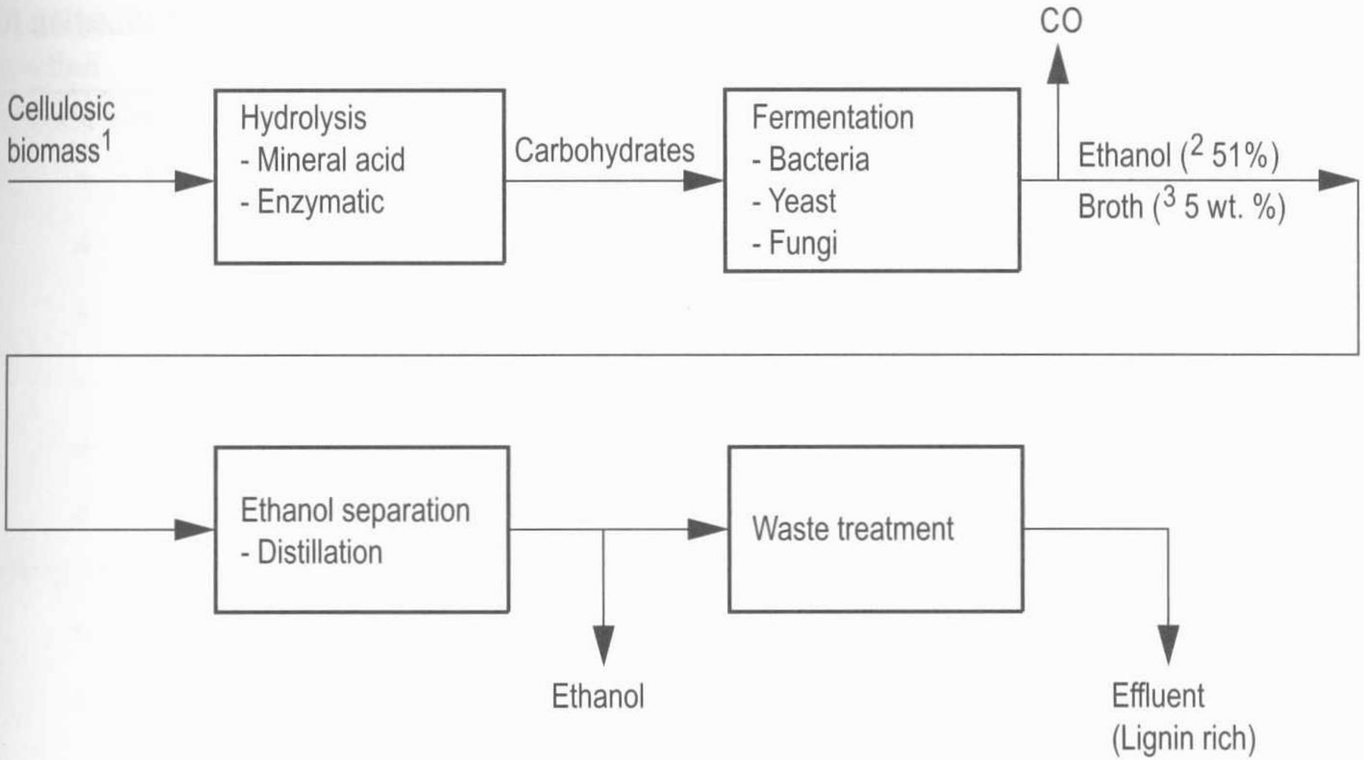


Figure 10.9. Schematic flowsheet for hydrolysis and fermentation of cellulosic materials to ethanol. Adapted from a discussion by Lynd (1996).

Notes:

1. Poor for softwoods conversion
2. Conversion of carbohydrate mass to ethanol
3. Typical ethanol concentration in broth

Table 10.8

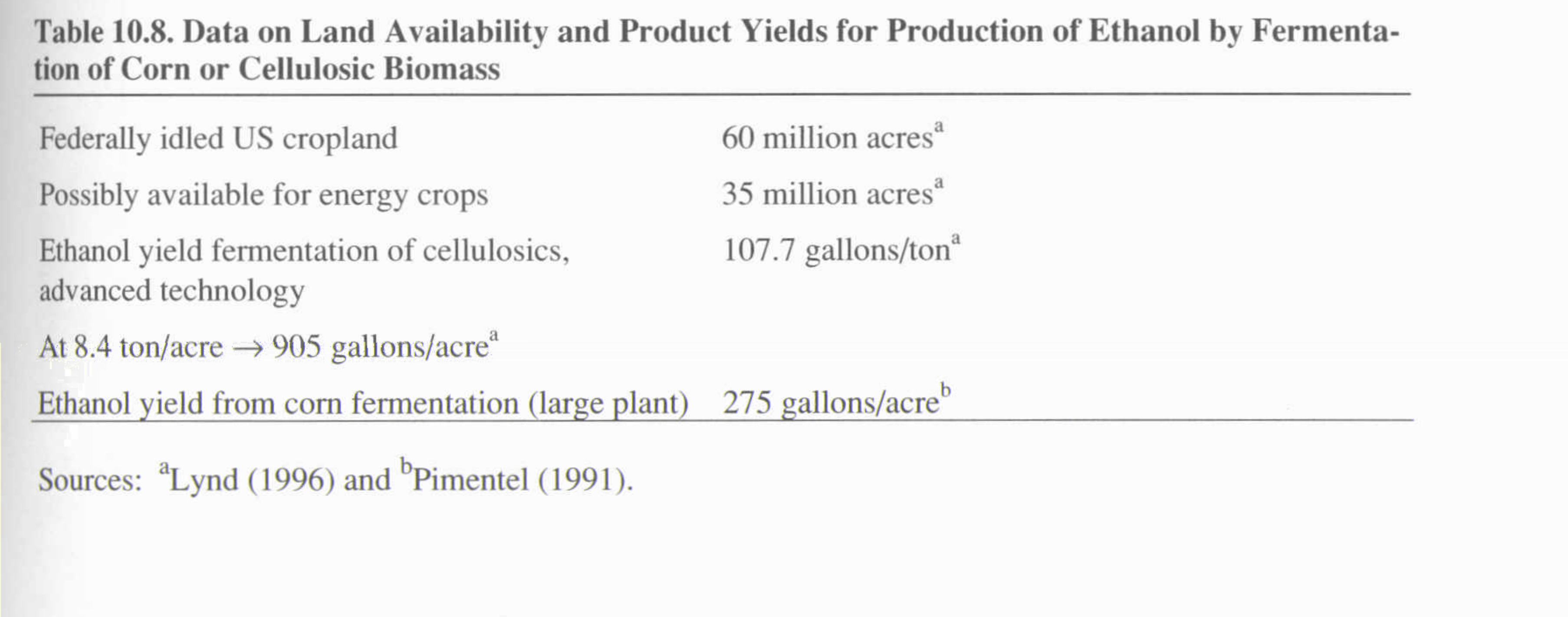


Table 10.8. Data on Land Availability and Product Yields for Production of Ethanol by Fermentation of Corn or Cellulosic Biomass

Federally idled US cropland	60 million acres[a]
Possibly available for energy crops	35 million acres[a]
Ethanol yield fermentation of cellulosics, advanced technology	107.7 gallons/ton[a]
At 8.4 ton/acre → 905 gallons/acre[a]	
Ethanol yield from corn fermentation (large plant)	275 gallons/acre[b]

Sources: [a]Lynd (1996) and [b]Pimentel (1991).

Environmental Issues

- **Tables 10.9 and 10.10 review the environmental impacts of biomass for energy production.**

Table 10.9

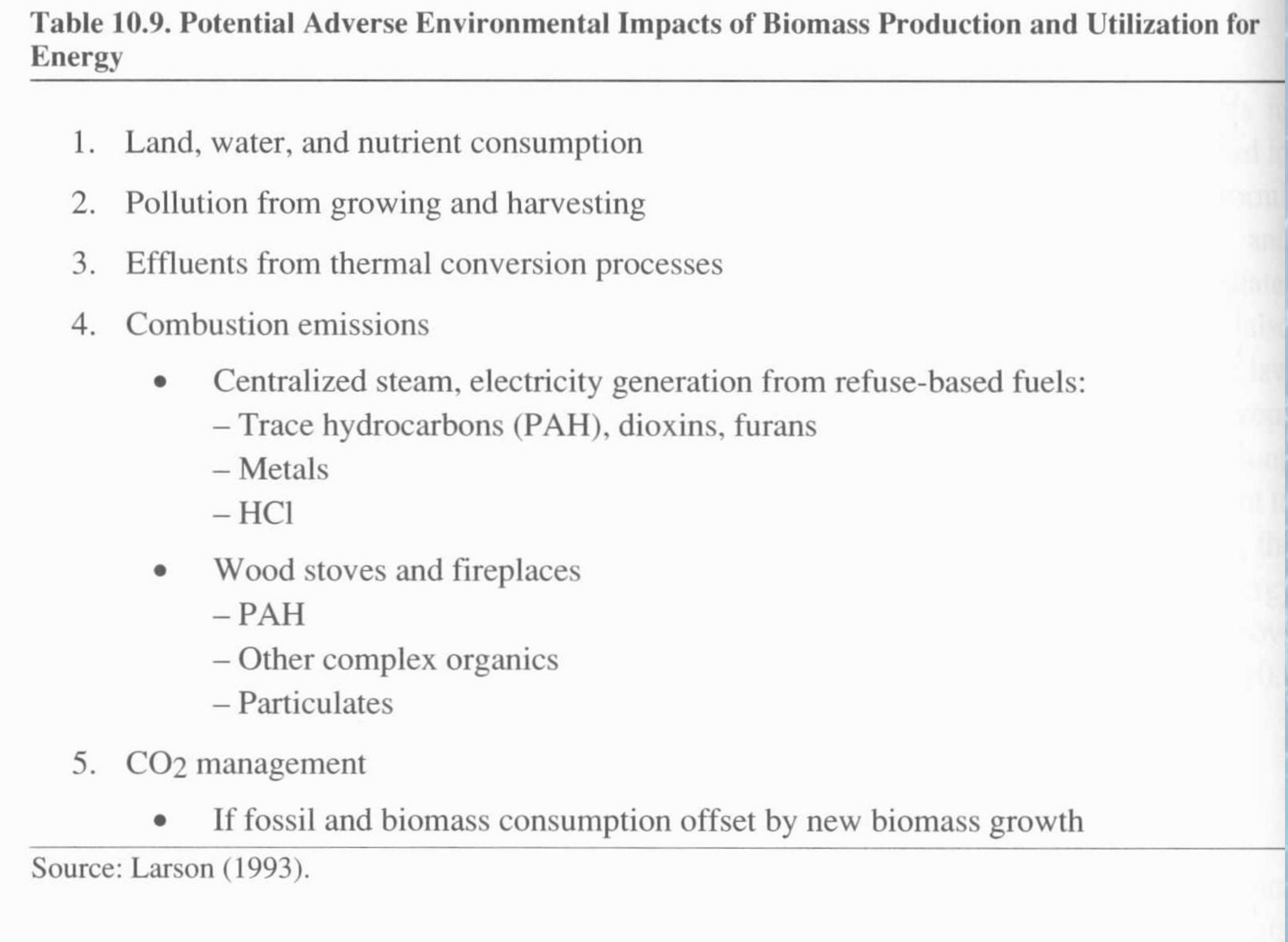


Table 10.9. Potential Adverse Environmental Impacts of Biomass Production and Utilization for Energy

1. Land, water, and nutrient consumption
2. Pollution from growing and harvesting
3. Effluents from thermal conversion processes
4. Combustion emissions
    - Centralized steam, electricity generation from refuse-based fuels:
      – Trace hydrocarbons (PAH), dioxins, furans
      – Metals
      – HCl
    - Wood stoves and fireplaces
      – PAH
      – Other complex organics
      – Particulates
5. CO_2 management
    - If fossil and biomass consumption offset by new biomass growth

Source: Larson (1993).

Table 10.10

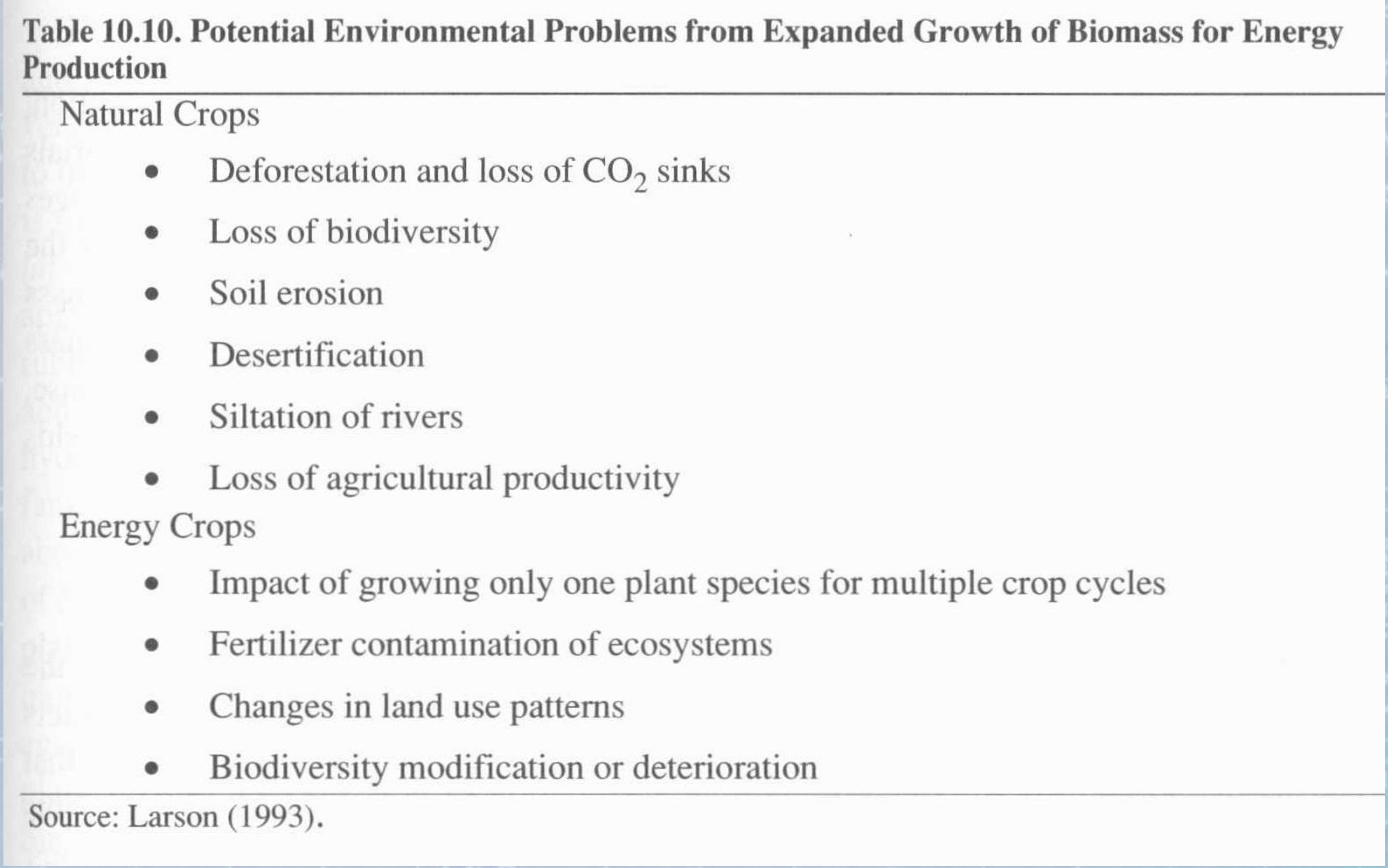


Table 10.10. Potential Environmental Problems from Expanded Growth of Biomass for Energy Production

Natural Crops

- Deforestation and loss of CO_2 sinks
- Loss of biodiversity
- Soil erosion
- Desertification
- Siltation of rivers
- Loss of agricultural productivity

Energy Crops

- Impact of growing only one plant species for multiple crop cycles
- Fertilizer contamination of ecosystems
- Changes in land use patterns
- Biodiversity modification or deterioration

Source: Larson (1993).

Economics

- A major factor in biomass energy economics is the high cost of producing and harvesting biomass.
- Recent increases in the prices of oil have made it feasible to explore the production of biofuels for transportation.
- Ethanol production from corn in the US is very inefficient compared to Brazil’s program and has considerable negative environmental impacts.
- The forest products industry has the greatest potential to become energy independent based on the biomass generated in their wastes.
- Continued concerns about the effects of carbon dioxide emissions from fossil fuel combustion are making biomass a more attractive alternative.
- Biotechnology may provide other alternatives to our fuel dilemma as genetic engineering is applied to the problem.