It is not widely appreciated that traditional plant-breeding techniques were effectively an imprecise form of genetic engineering: plants that have favourable characteristics and are therefore selected for breeding have favourable genotypes, which are therefore selectively replicated in future generations of plants. About half of past improvements in yields of rice, wheat and maize is due to genetic inputs. Recently, plant-breeding methods have been extended by two new ‘genetic’ techniques: tissue culture, which allows the crossing of favourable genotypes at cellular level to form new cultivars, and genetic modification, which involves the incorporation of individual genes directly into plant genomes. Despite the current outcry about GMOs (genetically modified organisms), a significant part of future improvement is likely to come from transgenically improved plants. Denis Murphy describes the enormous potential of ‘agbiotech’—the application of genetic techniques to improve food and non-food crop traits and yields in Chapter 13.

1.5 Energy and chemicals from biomass

Biomass was one of humanity’s earliest energy sources, and it remains an important resource today and for the future. Traditional plant biomass, particularly fuelwood, currently supplies a significant part of the energy needs of the developing world. Used and regrown sustainably, such energy sources could become an important component in a future CO_2-neutral energy economy. In the USA, biomass provides nearly 4% of final energy consumption. In the EU, biomass provided 7% of total primary production in 1997. Methane produced by landfill wastes is used to generate electricity as a matter of good practice in many countries.

Plant biomass resources include wood and wood wastes, agricultural crops and their residues, and aquatic plants and algae. Energy can be derived from biomass in three main ways:

- by direct combustion to provide heat and light as such, or to raise steam and hence generate electricity;
- by gasification to provide ‘biogas’, a combustible gas mixture predominantly consisting of H_2, CO and CO_2, that can be used for heating or electricity generation or converted to useful chemicals such as methanol;
- by fast pyrolysis at temperatures around 480–550 C, giving a high yield of ‘bio-oil’, an espresso-coffee-like liquid that can substitute for conventional fuel oil in transport and static applications.

Wood is substantially the largest source of biomass energy and indeed of renewable energy, providing more than twice the contribution of hydroelectricity worldwide. Energy crops (herbaceous plants and forest plantations grown specifically for their energy content) and biofuels[12] (solid, liquid or gaseous fuels made from biomass) are established or emerging features in several parts of the world. At the moment, biofuels and electricity made from biomass are expensive compared with conventional alternatives, and their use generally needs to be stimulated by subsidy or regulation. Future cost improvements should come from volume production, the development of more efficient chemical processes and the production of value-added chemicals.

The chemical composition of dry biomass varies somewhat with species but is roughly 75% carbohydrates or sugars and 25% lignin, with the empirical formula $C_3H_4O_2$. The main carbohydrates are cellulose—a polymer of glucose and the single most abundant product of photosynthesis—and hemicellulose. Because of their oxygen content, biomass and biofuels have a much lower calorific value (~18 GJ tonne^{-1} @100% dry matter) than conventional fuel oils (42–44 GJ tonne^{-1}). Biomass generally has low (<0.1%) sulphur content. Its nitrogen content depends on the protein content, which should be kept low to minimise the emission of NO_x on combustion.

Wood and straw are widely used as fuels. However, most other plant products are not suitable to be directly burned because they are too wet. Even fresh wood contains a considerable amount of water (30–50% by weight) and is best dried before use. Charcoal, produced by slow pyrolysis of wood in limited air, is used as a domestic and industrial fuel. In Brazil, the world's largest charcoal producer and consumer, charcoal is used in heavy industries such as pig-iron, steel making and cement manufacture.

Mike Bullard discusses energy crops in Chapter 9. These are (generally perennial) species that grow rapidly and can be harvested for their biomass annually or every few years. In northern Europe, the most promising energy crops are perceived to be coppiced willow or poplar, often referred to as short rotation coppice (SRC) or arable energy coppice (AEC). Other energy crops include conventional arable crops, novel annual crops such as sweet sorghum and perennial species such as elephant grass (*Miscanthus*). Although a native of Asia and Africa, *Miscanthus* grows well in temperate climates. Its C_4 photosynthetic pathway permits biomass yields of up to 55 t ha^{-1} in the UK (compare wheat, for example, with a theoretical maximum UK

[12] The terms biomass and biofuels are sometimes used interchangeably, but we distinguish here between the undifferentiated plant mass and well-defined chemical products derived from it.

yield of 33 t ha^{-1}). Field trials of such energy crops have been underway for some years in Europe and the USA. In developed countries, the economic viability of energy crops is generally marginal, or even poor at times of low energy prices. However, the growth of energy crops on idle or set-aside farmland could represent a major future opportunity if robust supply chains and markets can be established and costs held down.

Tony Bridgwater and Kyriakos Maniatis discuss biofuels in Chapter 10. The most widely used biofuel is ethanol, made by fermentation of starch crops. Brazil and USA have pioneered large-scale ethanol fuel programmes. Nearly 1.5 billion gallons of ethanol are produced from corn annually in the USA to blend with gasoline and reduce air pollution. Brazil began its Pro-Alcohol programme, making ethanol from sugar cane, to counter the oil price hikes of the 1970s and its dependency on imported oil. It is by far the world's major producer of cane alcohol, producing 10–15 million cubic metres annually and with significant export opportunities now opening up.

Biodiesel is another significant biofuel. Chemically, this consists of a range of fatty acid alkyl esters. It can be made from any vegetable oil, produced from any oil-bearing crop or microalga, by esterification with ethanol or methanol. The properties of biodiesel are quite similar to those of conventional diesel oil, enabling it to be used neat or in blends in conventional diesel engines. Rape methyl ester (RME) produced from oilseed rape is the main form of biodiesel in Europe and Canada. The USA produced about 5 billion gallons of biodiesel in 2000 from recycled cooking oils and soy oil.

Hydrogen, an important energy vector of the future, can be produced biologically under certain growth conditions by a range of photosynthetic microorganisms that contain either the hydrogenase enzyme or the closely related nitrogenase enzyme. Some strains of cyanobacteria have developed intracellular protective mechanisms that enable them to do this in air. Photosynthetic bacteria and algae have not developed protective systems, and can produce H_2 under anaerobic but not aerobic conditions. Historically, these cultures have been easily poisoned and short-lived, but recent cyanobacterial cultures are encouragingly robust and other tricks are being used to enhance H_2 evolution from green algae. Boichenko, Greenbaum and Seibert discuss progress in Chapter 8.

Many other chemicals and products can be derived from biomass. Cellulose fibres from wood are used to make paper and textiles, natural pharmaceuticals can be extracted from many plants. In Chapter 7, Rosa Martinez and Zvi Dubinsky discuss the range of products that can be derived from algae.

Statistics on the use and trends in use of biomass for energy generation are needed in energy and CO_2 emissions modelling, particularly where developing countries are moving from traditional biomass use to fossil fuel use. Unfortunately, reliable data do not generally exist. Traditional biomass (fuelwood and crop and animal residues) is either collected by the user or traded in highly informal markets. The volume of these transactions is not metered and can only be roughly estimated from spot consumer surveys. Statistics on commercial use of biomass in forestry, paper and sugar industries and large-scale CHP and power generation are better.

Table 1.1 showed what are probably still the most reliable statistics on global and regional biomass use, derived from two workshops held by the IEA in 1997 and 1998. According to this survey, biomass accounts for ~11% of world total primary energy supply (TPES) and ~14% of world total final consumption (TFC). Nearly all of this consumption is in non-OECD (developing) countries, where biomass comprises ~20% of TPES and ~27% of TFC. (Most biomass is simply burned in such countries, rather than being converted to derived biofuels or used to generate electricity, so the proportion of biomass in final energy use is higher than in primary supply.)

The main sources of national biomass data are the UN's Food & Agriculture Organisation (*www.fao.org*) and Energy Statistics Division and, for Asia, the Center for Energy-Environment Research and Development (*www.ceerd.ait.ac.th/*). The FAO (*www.fao.org/waicent/faoinfo/forestry/energy/)* has made considerable efforts to gather statistics on forest woodfuel, through its series of publications *Wood Energy Today for Tomorrow* (FAO, 1997–1999). Other useful sources of information are the latest biennial survey of the World Energy Council (WEC, 2001), the world biomass scenarios of Hoogwijk *et al.* (2001) and the final paper by that most indefatigable of champions of biomass, the late Professor David Hall of King's College, London (Hall *et al.*, 2000).

References

Abrahams J. P., Leslie A. G. W., Lutter R. and Walker J. E. (1994), 'Structure at 2.8 Å resolution of F_1–ATPase from bovine heart mitochondria', *Nature* **370**, 621–628.

Andersson B., Salter H. A. and Barber J. (1996), *Molecular Genetics of Photosynthesis*, Oxford University Press, Oxford.

Arnon D. I. (1951), 'Extracellular photosynthesis reactions', *Nature* **167**, 1008–1010.

Arnon D. I., Mitsui A. and Paneque A. (1961), 'Photoproduction of hydrogen gas coupled with photosynthetic phosphorylation', *Science* **134**, 1425.

Arnon D. I., Whatley F. R. and Allen M. B. (1954), 'Photosynthesis by isolated chloroplasts. II. Photosynthetic phosphorylation, the conversion of light into phosphate-bond energy', *J. Am. Chem. Soc*. **76**, 6324–6329.

Barber J. and Archer M. D. (2001), 'P680, the primary electron donor of Photosystem II', *J. Photochem. Photobiol*. **A142**, 97–106.

Bassham J. A. and Calvin M. (1957), *The Path of Carbon in Photosynthesis*, Prentice-Hall, Englewood Cliffs, N.J.

Bassham J. A. (1976), 'Mechanism and efficiency of photosynthesis in green plants', *Symp. Clean Fuels from Biomass, Sewage, Urban Refuse and Agricultural Wastes*, Orlando, Florida, Institute of Gas Technology, Chicago, pp. 205–208.

Benemann J. R., Berenson J. A., Kaplan N. D. and Kamen M. D. (1973), 'Hydrogen evolution by a chloroplast–ferredoxin–hydrogenase system', *Proc. Nat. Acad. Sci. USA* **70**, 2317–2320.

Blankenship R. E. (2002), *Molecular Mechanisms of Photosynthesis,* Blackwell Science Ltd., Oxford.

Boardman N. K. and Larkum A. W. D. (1975), 'Energy exchange in the living world', in Messel H. and Butler S. T., eds., *Solar Energy*, Pergamon Press, Oxford, pp. 125–144.

Bolton J. R. (1979), 'Solar energy conversion in photosynthesis—features relevant to artificial systems for the photochemical conversion of solar energy', in King J. B., Hautala R. R. and Kutal C. R., eds., *The Chemical Conversion and Storage of Solar Energy*, Humana Press, Clifton, N.J., pp. 31–50.

Climate Change (2001): The Scientific Basis, Houghton J. T. *et al.*, eds., Cambridge University Press, Cambridge.

Deisenhofer J., Epp O., Miki K., Huber R. and Michel H. (1984), 'X-ray structure analysis of a membrane and protein complex. Electron density maps at 3X resolution and a model of the chromophores of the photosynthetic reaction centre from *Rhodopseudomonas viridis*', *J. Mol. Biol.* **80**, 385–398.

Deisenhofer J., Epp O., Miki K., Huber R. and Michel H. (1985), 'Structure of the protein subunits in the photosynthetic reaction centre of *Rhodopseudomonas viridis* at 3Å resolution', *Nature* **318**, 618–624.

Deisenhofer J.and Norris J. R. (1993 and 1997), eds., *The Photosynthetic Reaction Centre*, Vol. 1 (1993) and Vol. 2 (1997), Academic Press, New York.

Emerson R. and Arnold W. (1932), 'A separation of the reactions in photosynthesis by means of intermittent light', *J. Gen. Physiol.* **15**, 391–420.

Falkowski P. G. and Raven J. (1997), *Aquatic Photosynthesis*, Blackwell Science, Oxford.

FAO (1997–1999), *The Role of Wood Energy in Europe and the OECD*, van den Broek R., March 1997; *The Role of Wood Energy in Asia*, Lefevre T., November 1997; *The Role of Wood Energy in Africa*, Amous S., May 1999.

Ferreira K. N., Iverson T., Maghlaoui K., Barber J. and Iwata S. (2004), 'Architecture of the photosynthetic oxygen-evolving center', *Sciencexpress*, 5 February 2004/ *Science* 1093087.

Frenkel A. W. (1954), 'Light-induced photophosphorylation by cell-free preparations of photosynthetic bacteria', *J. Am. Chem. Soc.* **76**, 5568–5569.

Gaffron H. and Wohl K. (1936), 'Zur Theorie der Assimilation', *Naturwissenschaften* **24**, 81–90, 103–107.

Gaffron H. and Rubin J. (1942), 'Fermentation and photochemical production of hydrogen in algae', *J. Gen. Physiol.* **26**, 219–240.

Hall D. O. (1977), 'Will photosynthesis solve the energy problem?', in Bolton J. R., ed., *Solar Power and Fuels*, Academic Press, New York, pp. 27–52.

Hall D. O. and Rao K. K. (1999, 6th. ed.), *Photosynthesis*, Cambridge University Press, Cambridge.

Hall D. O., House J. I. and Scrase I. (2000), 'Overview of biomass energy', Ch. 1 in *Industrial Uses of Biomass Energy*, Rosillo-Calle F., Bajay S. and Rothman H., eds., Taylor & Francis, London, pp. 1–26.

Hatch M. D. and Slack C. R. (1966), 'Photosynthesis by sugar cane leaves: a new carboxylation reaction and the pathway of sugar formation', *Biochem. J.* **101**, 103–111.

Hill R. (1937), 'Oxygen evolved by isolated chloroplasts', *Nature* **139**, 881–882.

Hill R. and Bendall F. (1960), 'Function of the two cytochrome components of chloroplasts: a working hypothesis', *Nature* **186**, 136–137.

Hoogwijk M., van dem Broek R., Berndes G. and Faaij A. (2001), 'A review of assessments on the future contribution of biomass energy', *Proc. 1st. World Conf. on Biomass for Energy and Industry*, James & James, Vol. 1, pp. 296–299.

Iwata S., Lee J. W., Okada K., Lee J. K., Iwata M., Rasmussen B., Link T. A., Ramaswamy S. and Jap B. K. (1998), 'Complete structure of the 11-subunit bovine mitochrondrial cytochrome *bc*(1) complex', *Science* **281**, 64–71.

Joliot P., Barbieri G. and Charbaud R. (1969), 'Un nouveau modele des centres photochimique du systeme II', *Photochem. Photobiol.* **10**, 309–329.

Jordan P., Fromme P., Witt H. T., Klukas O., Saenger W. and Krauss N. (2001), 'Three-dimensional structure of cyanobacterial photosystem I at 2.5 X resolution', *Nature* **411**, 909–917.

Kamiya N. and Shen J. R. (2003), ‘Crystal structure of oxygen-evolving photosystem II from *Thermosynechococcus vulcanus* at 3.7 Å resolution’, *Proc. Nat. Acad. Sci. USA* **100**, 989–102.

Ke B. (2001), Photosynthesis: Photobiochemistry and Photobiophysics, Kluwer Academic Press, New York.

Kok B., Forbush B. and McGloin M. (1970), ‘Cooperation of charges in photosynthetic O_2 evolution. 1. A linear four step mechanism’, *Photochem. Photobiol*. **11**, 457–475.

La Roche J., van der Staay G. W. M., Partensky F., Ducret A., Aabersold R., Li R., Golden S. S., Hiller R. G., Wrench P. M., Larkum A. W. D. and Green B. R. (1996), Independent evolution of the prochlorophyte and green plant chlorophyll *a/b* light-harvesting proteins’, *Proc. Nat. Acad. Sci. USA* **93**, 15244–15248.

Lewin R. A. (1976), ‘Prochlorophyta as a proposed new division of algae,’ *Nature* **261**, 697–698.

Maynard Smith J. and Szathm<ry E. (1999), *The Origins of Life*, Oxford University Press, Oxford.

Michel H. (1982), ‘Three-dimensional crystals of a membrane–protein complex. The photosynthetic reaction centre from *Rhodopseudomonas viridis*’, *J. Mol. Biol.* **158**, 567–572.

Mitchell P. (1966), ‘Chemiosmotic coupling in oxidative and photosynthetic phosphorylation’, *Biol. Rev*. **41**, 445–502.

Partensky F, Hess W. R. and Vaulot D. (1999), ‘*Prochlorococcus*, a marine photosynthetic prokaryote of global significance’, *Microbiol. Mol. Biol. Rev*. **63**, 106–127.

Pirson A. (1937), ‘A study of the nutrition and metabolism of *Fontinalis Chlorella*’, *Z. Bot.* **31**, 193–267.

Rhee K.-H., Morris E. P., Barber J. and Kuehlbrandt W. (1998), ‘Three dimensional structure of the PSII reaction centre at 8 Å’, *Nature* **396**, 282–286.

Royal Society (2001), ‘The role of land carbon in mitigating global climate change’, The Royal Society (*www.royalsoc.ac.uk*).

Ruben S., Randall M., Kamen M. D. and Hyde J. L. (1941), ‘Heavy oxygen (^{18}O) as tracer in the study of photosynthesis’, *J. Am. Chem. Soc*. **63**, 877–878.

Schneider T. R. (1973), ‘Efficiency of photosynthesis as a solar energy converter’, *Energy Conversion* **13**, 77–85.

Schubert W. D., Klukas O., Saenger W., Witt H. T., Fromme P. and Krauss N. (1998), ‘A common ancestor for oxygenic and anoxygenic photosynthetic systems: a comparison based on the structural model of photosystem I’, *J. Mol. Biol*. **280**, 297–314

Tolmach L. J. (1951), ‘Effect of triphosphopyridine nucleotide upon oxygen evolution and carbon dioxide fixation by illuminated chloroplasts’, *Nature* **167**, 946–948.

Tommos C. and Babcock G. T. (2000), ‘Proton and hydrogen currents in photosynthetic water oxidation’, *Biochim. Biophys. Acta* **1458**, 199–219.

van Niel C. B. (1935), ‘Photosynthesis of bacteria’, in *Cold Spring Harbor Symp. Quant. Biol*. **3**, 138.

Vishniac W. and Ochoa S. (1951), ‘Photochemical reduction of pyridine nucleotides by spinach grana and coupled carbon dioxide fixation’, *Nature* **167**, 768–769.

WEC (2001), *Survey of Energy Resources*, World Energy Council (*www.worldenergy.org*).

Woese C. R. (2000), ‘Interpreting the universal phylogenetic tree’, *Proc. Nat. Acad. Sci. USA* **97**, 8392–8396.

Zelitch I. (1971), *Photosynthesis, Photorespiration and Plant Productivity*, Academic Press, New York.

Zhang Z. L., Huang L. S., Shulmeister V. M., Chi Y. I., Kim K. K., Hung L. W., Crofts A. R., Berry E. A. and Kim S. H. (1998), ‘Electron transfer by domain movement in cytochrome bc_1’, *Nature* **392**, 677–684.

Zouni A., Witt H. T., Kern J., Fromme P., Krauss N., Saenger W. and Orth P. (2001), ‘Crystal structure of photosystem II from *Synechococcus elongatus* at 3.8 Å resolution’, *Nature* **409**, 739–743.