CHAPTER

11

Environmental Impact of the Bioeconomy

11.1 Introduction

Much has been made of the negative environmental impact of using fossil fuels. The assumption has often been made that anything that reduces use of fossil fuels will therefore benefit the environment. The reality is much more complicated—every technology introduces both benefits and costs whose net impact depends upon what is most valued by society. Exploitation of biorenewable resources is no exception. Agriculture has been blamed for desertification in Africa while demand for fuel wood was clearly responsible for deforestation of large parts of Europe.

This chapter explores some of the potential environmental impacts of using biorenewable resources in the production of fuels, chemicals, energy, and fibers. These impacts are not always readily apparent; for example, the role of chlorofluorocarbons, once commonly used as refrigerants and blowing agents, in atmospheric ozone depletion was not recognized until decades after their commercial development. Thus, there is a tendency to err on the side of caution in assessing the potential negative impacts of new technologies on the environment. This chapter organizes the topic in terms of the broad areas of plant science, crop production, processing, and utilization of biobased products.

11.2 Plant Science

The potential impact of plant science on the environment is among the most contentious debates in modern society. The prospect of creating new plants by the application of biotechnology and releasing them to the biosphere or introducing them to the human food supply concerns many people. Particularly in Western nations, whose people enjoy secure food supplies and have the leisure and financial

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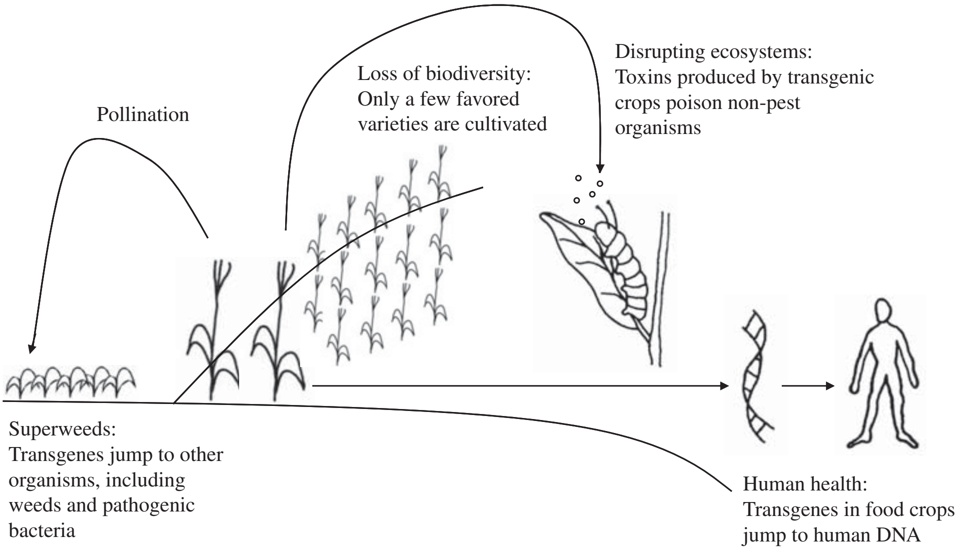

Fig. 11.1 Potential environmental impacts of plant science.

resources to appreciate pristine natural environments, there has arisen the notion of "Frankenfood," a man-made plant with toxins that poison the food supply or that is so prolific that it upsets the balance of nature.

Application of biotechnology to plant science offers several opportunities for plant improvements, including resistance to herbicides, protection against insects and other pests, hardiness against frost, and the manufacture of valuable products in plants. The latter of these possibilities, many believe, is the key to future growth in the development of biobased products. The concerns about the environmental impact of transgenic crops must be addressed early in their development if this future is to be realized. Some of the most prominent environmental concerns about transgenic crops are illustrated in Figure 11.1 and discussed in the following paragraphs.

As described in Chapter 5, the process of developing a transgenic plant requires selection of plant cells that have been successfully transformed; that is, those that have incorporated the transgene. This is commonly accomplished by inclusion of a selectable marker gene in the constructed transgene that is resistance to an herbicide or an antibiotic. Thus, application of the herbicide or antibiotic to regenerated plants kills those that do not contain the transgene, allowing the transgenic plants to be identified and selected. The prospect of these resistant genes being transferred to wild plants by pollination or to bacteria by the same kind of gene transfer between bacteria and plant cells that are frequently used to produce transgenic crops is disturbing to many people. Transfer of herbicide resistance to weeds would be a serious threat to agriculture while transfer of antibody resistance to pathogens would threaten human health.

Transfer of herbicide resistance is a distinct possibility if transgenic crops are grown in close proximity to closely related weed species. For example, gene movements between wild mustard growing among a crop of canola and between jointed goatgrass growing among a crop of wheat have been demonstrated, raising the prospects for "superweeds." The transfer of antibiotic resistance to pathogenic bacteria is an extremely unlikely event but cannot be completely ruled out. For these reasons, alternative selection methods, such as marker genes that cause a transformed plant to fluoresce when exposed to ultraviolet light, are under development. Of course, the transfer of genes that are specifically added to make a plant resistance to herbicides or to attack by insects cannot be prevented in this manner. In this case, more sophisticated approaches to preventing the creation of superweeds are required. For example, herbicide-resistant genes could be linked to other genes that are harmless to a crop but damaging to a weed that might incorporate the transgene.

Another concern is that parts of a transgene inserted into food crops might escape the digestive tract and be inserted into human chromosomes. A specific example cited by critics of transgenic crops is the cauliflower mosaic virus (CaMV), often used as a promoter sequence in transgenic crops (recall that a promoter sequence is the on/off switch that controls where the plant gene will be expressed). Research on plasmid DNA in rice is cited as evidence that the CaMV promoter can insert itself into strands of DNA. However, the chain of events necessary for this to occur in human DNA is unlikely and has never been observed. CaMV infects several common crop plants, including cauliflower, broccoli, cabbage, bok choy, and canola, which have been consumed by animals and humans for centuries with no documented negative effects on health.

One well-publicized concern is that transgenic crops might threaten other organisms in an ecosystem by introducing toxic substances. Researchers have documented in laboratory trials that pollen from Bt corn, one of the first commercial transgenic crops, is toxic to monarch butterfly larvae. Bt corn was genetically engineered to contain a substance toxic to natural predators of the corn plant, so the fact that Bt corn pollen was toxic to insects was not particularly surprising. However, this demonstration raised the possibility that pollen drifting from a cornfield to milkweed growing in adjacent fields would poison monarch butterfly larvae that feed on milkweed plants, their principle source of nourishment. Follow-up studies indicate that pollen drift is unlikely to produce toxic levels of Bt corn pollen in adjacent fields. The original laboratory work, though, does demonstrate the delicate interplay between introduced plants and their environment.

Another argument cautions that transgenic crops will ultimately reduce biodiversity as they replace traditional crops. Inevitably, this will be true since the history of agriculture even before transgenic crops might best be described as the adoption of a few superior varieties that replace a wider selection of traditional crops. The solution to loss of biodiversity is not to limit choices in agriculture but rather to establish collections of rare and obsolete varieties to serve as gene banks.

In developing transgenic crops, risk assessment should evaluate the following questions regarding their release to the environment: Does the introduction of a transgenic plant with resistance to a particular pest or disease exacerbate the emergence of new pests or diseases that are worse than the original? If a transgenic trait is transferred to a wild species, does their geographical expansion represent a threat to biological diversity? Would adoption of stress-tolerant plants lead to significant destruction of natural ecosystems?

11.3 Production

Agriculture can have either positive or negative impacts on the environment depending upon how it is practiced. Early cultivation of cotton and tobacco in the southern United States was notorious for quickly depleting soil fertility, requiring frequent opening of new lands for production of these crops. As illustrated in Figure 11.2, unsustainable agricultural practices result in loss of soil fertility, soil erosion, water pollution, air pollution, reduced biodiversity, and net positive emission of greenhouse gases from the soil to the atmosphere. Careful application of conservation principles can avoid or even reverse these impacts of agriculture.

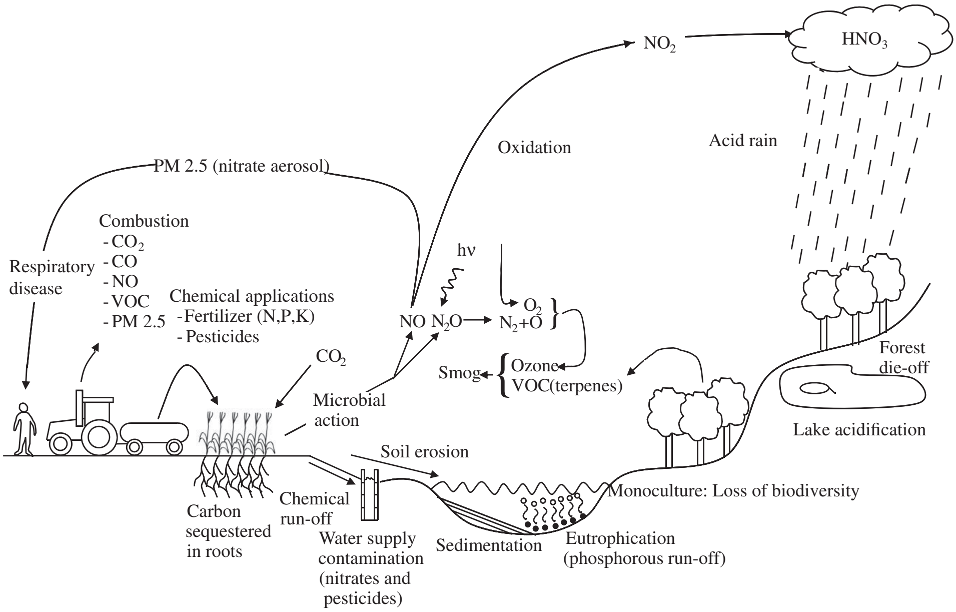

FIG. 11.2 Potential environmental impacts of crop production.

11.3.1 Soil Fertility

Soil fertility is primarily a function of the amounts of organic carbon (also known as humus), nitrogen (N), phosphorous (P), and potassium (K) in the soil. The amount of organic carbon in the soil increases or decreases from year to year depending on tillage practices. The amount of inorganic nutrients (N–P–K) in the soils of natural ecosystems is determined by a balance among wind and water transport processes and uptake by standing biomass.

Organic carbon affects soil fertility in several ways including increasing water retention capacity and gas permeability and improving the availability of inorganic nutrients to plant roots. Organic carbon is a natural product from the decay of plant material in oxygen-poor environments. This includes roots as well as aboveground stems and leaves that accumulate on the surface of soil as thatch or that is submerged in waterlogged soils. Plant material exposed to air will eventually oxidize to carbon dioxide, which is released to the atmosphere. Organic carbon was accumulated in many meters of depth in the tall grass prairies of the Midwestern United States in the period between the last Ice Age and the present era. This deep, black soil is the basis for the highly productive agriculture system in the United States. Ironically, the process of plowing these soils for agriculture exposed the buried carbon to oxidation, contributing substantially to the loss in fertility of these soils during the past 150 years. Modern conservation tillage practices can reduce and even reverse these losses.

Intensive agriculture disrupts the balance of inorganic nutrients in the soil: uptake of nitrogen, phosphorous, and potassium by standing biomass that is subsequently removed as crop leads to depletion of these nutrients from the soil faster than transport by wind or water can replace them. Consequently, inorganic nutrients must be periodically replaced by application of fertilizer. Cropping systems have widely varying fertilizer requirements, as indicated in Table 11.1. Corn, for example, is notable for its demand for nitrogen, requiring on the order of

Table 11.1 Environmental impacts of different kinds of crops

Cropping System	Soil Erosion Rate (Mg/ha/year)	N–P–K Application Rate (kg/ha/year)	Herbicide Application Rate (kg/ha/year)	Insecticide Application Rate (kg/ha/year)
Annual crops				
Corn	21.8	135–60–80	3.06	0.38
Soybeans	40.9	20–45–70	1.83	0.16
Perennial crops				
HEC	0.2	50–60–60	0.25	0.02
SRWC	2.0	60–15–15	0.39	0.01

Source: Hohenstein, W.G. and Wright, L.L. (1994) Biomass energy production in the United States: an overview. *Biomass and Bioenergy*, 6, 161–173.

135 kg/ha/year compared to only 50–60 kg/ha/year for herbaceous energy crops (HEC) and short rotation woody crops (SRWC). At the other extreme is soybean, requiring only 20 kg/ha/year of nitrogen as a result of this plant's ability to synthesize nitrogen compounds from atmospheric nitrogen through the action of symbiotic bacteria in its roots. Not only is fertilizer application expensive and energy intensive (especially nitrogen) but it also impacts water pollution, as subsequently described.

Some dedicated energy crops have the potential for improving soil fertility. Those that are perennial crops, once established, do not require annual tilling of the soil, which contributes to the loss of soil carbon by both oxidation and erosion. As Table 11.1 shows, these perennial crops also have relatively modest fertilizer requirements, especially compared to corn; thus, they deplete inorganic nutrients at relatively lesser rates. In general, establishment of dedicated energy crops in place of conventional row crops will improve soil fertility. However, this may not be true if the dedicated energy crops are established on fallow lands or pasture, especially in the early years of establishment.

11.3.2 Soil Erosion

Soil erosion is the transport of soil from one location to another, either by wind or by water. In the process, the losses of organic carbon and inorganic nutrients from one location are gained by other locations; thus, erosion is not inherently bad. In practice, though, the net effect of soil erosion is to rob fertility from lands under intensive agriculture, which reduces crop productivity and distributes soil and nutrients in unwanted locations, thus making them pollutants. Table 11.1 shows that cropping systems employing perennial crops have soil erosion rates that are one to two orders of magnitude less than for row crops such as corn and soybeans. In fact, during the first two years of establishment of perennial crops, erosion rates can be comparable to those for row crops, but these rates decrease dramatically after root systems develop and, in the case of woody crops, tree canopies close. Use of ground covers might further reduce erosion for dedicated energy crops.

11.3.3 Water Pollution

Water pollution arises from both water-induced soil erosion and leaching of chemicals (inorganic nutrients, herbicides, and insecticides) from soils. Transport of soil from cultivated fields into waterways is responsible for the notoriously muddy rivers and streams of the Midwestern United States. Suspended solids can dramatically change aquatic ecosystems, driving out game fish, for example, which are replaced by bottom feeders. Soils washed into reservoirs and lakes drop out of suspension to form sediments that seriously reduce the water holding capacity of these impoundments, affecting both animal and human activities. Suspensions of soil can also facilitate transport of agricultural chemicals, which can attach to individual soil particles.

Leaching of chemicals from soils is roughly proportional to their application rates to cropland. Although comprehensive data is not available, as little as 40% of nitrogen applied to an annual crop is incorporated into plant matter, the balance being volatilized or leached from the soil. Table 11.1 indicates that leaching of inorganic nutrients, herbicides, and insecticides can be expected to be considerably worse for row crops than perennial energy crops.

Ammonia, the usual form of nitrogen in fertilizer, is oxidized to nitrates when exposed to air. Nitrates are readily leached from soils and can appear in both well water and river water at concentrations exceeding the 10-ppm human health standard set by the US Environmental Protection Agency (EPA). Human babies are susceptible to nitrate poisoning in the first few months of life when bacteria living in their digestive tracts convert nitrate to nitrite, which binds to hemoglobin and destroys its oxygen-carrying ability. Known as "blue baby" disease, a poisoned infant gradually suffocates. By the time a child reaches 6 months of age, stomach acids are sufficiently strong to kill the offending bacteria, and the disease is no longer a concern.

Phosphorous, which binds tightly to soil particles, is washed from fields as a result of soil erosion. Phosphorous represents a particular threat to aquatic ecosystems. In a process known as eutrophication, phosphorous promotes the rapid growth of algae near the surface of bodies of water. Eventually the algae die and their decomposition reduces dissolved oxygen to levels too low to support aquatic organisms, a condition known as hypoxia. The result is a general die-off in the body of water. The problem can reappear periodically since phosphorous accumulates in the sediments of lakes and streams. Rapid run-off during a storm can stir up sediment and release phosphorous in another cycle of eutrophication.

Potassium in drinking water is not regulated. The World Health Organization does not consider this chemical to have any impact on drinking water quality or on human health.

Herbicides and insecticides are, by definition, toxic chemicals used to control plant and animal pests. Their environmental and health effects at low concentrations are not well known, but they have been implicated as potential carcinogens and endocrine disrupters. They can be directly leached from the soil or transported by attachment to eroded soil particles. Most problems with pollution from pesticides arise from point source emissions such as occur from accidental spills or improper disposal of chemical containers. However, nonpoint source pollution can result from heavy rainfalls that occur immediately after application of pesticides to a field. Both herbicides and insecticides have been detected year-round in unconfined aquifers at very high concentrations (hundreds of parts per million). The lower pesticide application rates and the lower soil erosion rates associated with perennial energy crops suggest that pesticide pollution will be considerably less than for conventional row crops.

11.3.4 Air Pollution

The contribution of crop production to air pollution is of two types: exhaust emissions from tractors and other production machinery and dust and gas arising from tilled soils. Exhaust emissions from internal combustion engines include nitrogen oxides, carbon monoxide, unburned hydrocarbons, and fine particulate. The impacts of these emissions on the environment are detailed in a subsequent section; however, the total emissions from production machinery are small and diffuse compared to those from the transportation and utility sectors of the economy.

Potentially more significant is the contribution of soil tillage to air pollution, which generates both particulate and gaseous pollutants. Particulate pollutants are classified as either primary or secondary particulate matter (PM), depending upon its origin. Primary PM is emitted to the atmosphere as particles, while secondary PM is frequently formed in the atmosphere by chemical reaction of gaseous pollutants. An example of primary PM is dust stirred up from dry soil when it is plowed. Primary PM produces relatively course particles, on the order of 10 μm in size.

A prominent instance of secondary PM is nitrate aerosols, which are formed by the oxidation of combustion-generated nitric oxide that has been emitted to the atmosphere. Secondary PM is produced as very fine particles, which, for regulatory purposes, is defined as being less than 2.5 μm in size. Such fine particle matter, designated as PM 2.5, is readily respired into the lungs but not out of them. PM 2.5 recently has been implicated in respiratory disease and is a regulated pollutant for some industries.

Wind-blown dust from agriculture can travel hundreds and even thousands of miles. Although a nuisance, this dust is mostly coarse PM, which is not thought to represent a health hazard. Careful soil management practices can mitigate nuisance dust from agriculture. However, agriculture can also produce secondary PM, which is mostly PM 2.5. Ammonia applied to soil as nitrogen fertilizer can escape as gas into the atmosphere where it reacts to form fine nitrate aerosol. Agriculture is not currently regulated for fine PM.

Several gaseous pollutants can arise from cultivation. Soil nitrogen, either from nitrogen-fixing bacteria or from synthetic fertilizers, is converted to nitric oxide (NO) and nitrous oxide (N_2O) by microbial processes in wet, anaerobic soils. Microbial processes in tilled soils also produce methane, a greenhouse gas; however, the vast majority of methane emissions come from animals and anaerobic digestion of animal wastes. Manure from livestock in the United States is estimated to emit about 3 million metric tons of methane annually and account for approximately 10% of the total US methane emissions.

Nitric oxide released to the atmosphere is further oxidized to nitrogen dioxide (NO_2), which results in two pollution problems. A strong oxidizing agent, NO_2 reacts to form nitric acid, which dissolves in water droplets to form acid rain. Environmental degradation from acid rain includes acidification of lakes, which kills aquatic organisms, and damage to forests and crops. Nitrogen dioxide is also critical to the formation of ground-level ozone (O_3) in a two-step reaction mediated by sunlight:

$$NO_2 + h\nu \rightarrow NO + O \tag{11.1}$$

$$O_2 + O \rightarrow O_3 \tag{11.2}$$

Ground-level ozone, also known as urban ozone, is a health hazard that has proved a serious concern in large cities where NO is formed by automobiles and power plants. It also reacts with volatile organic hydrocarbons emitted from automobiles to form photochemical smog, a mixture of aldehydes, acid gases, and peroxyacetal nitrate ($C_2H_3O_5N$) that forms a brown hazy smudge over many large cities. Smog is not only unsightly but also irritates the eyes and lungs.

Although nitrogen oxide emissions in large urban areas are clearly a major problem, it is not known whether nitrogen oxide emissions from agricultural lands are a substantial problem since little information is available on the subject. It is expected, though, that emissions from dedicated energy crops will be less than from row crops and more than from temperate forests.

Nitrous oxide is relatively stable to chemical reaction compared to NO, but it is a strong greenhouse gas. The background level of N_2O in the atmosphere has been increasing during historical times. Some researchers attribute this trend to intensive agriculture. Its possible role in global warming is discussed in a later paragraph.

Volatile organic compounds (VOC) are also emitted from growing plants. Consisting of mostly terpenes, these molecules can react with nitrogen oxides in a process akin to smog formation in large cities to produce a bluish haze, which gives the Smoky Mountains their name. This picturesque effect may be less appealing if anthropogenic emissions of nitrogen dioxides combine with biogenic emissions of VOCs in agricultural and pristine regions.

11.3.5 Biodiversity

Biodiversity describes an environment characterized by large numbers of different species of plants and animals. Agriculture traditionally has strived for just the opposite—a monoculture of one plant species, where other plants and animals are considered pests. Production of dedicated energy crops has some prospects for improving biodiversity in the agricultural landscape. Certainly, the meadow-like setting of fields planted to perennial grasses and the forest-like setting of tree plantations more closely resemble natural ecosystems than do row crops.

In fact, there are advantages in encouraging a certain degree of biodiversity in dedicated feedstock supply systems. Multi-species production systems could reduce the risks associated with pests. Adding nitrogen-fixing plants could reduce fertilizer applications. Other plants might provide superior erosion control during establishment.

11.3.6 Greenhouse Gas Emissions

Greenhouse gases are gases that interact with infrared radiation emitted from the Earth in such a way as to trap this radiant energy in the Earth's atmosphere. Greenhouse gases are important in moderating the Earth's temperature, keeping it in a zone that is conducive to life. The principal greenhouse gases are water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons, the latter arising solely from human activity while the others have both anthropogenic and biogenic origins. As the concentrations of these gases increase, the temperature of the Earth is expected to increase, although the sensitivity of temperature to greenhouse gas concentrations is the subject of much debate.

What is known with certainty is that carbon dioxide in the atmosphere has increased about 25% since measurements were first taken in 1959 and that average global temperature has been increasing steadily for the last 30 years. Other greenhouse gases are also increasing, although carbon dioxide is thought to be the most important determinant to global temperature modulation. There is little debate that increases in atmospheric greenhouse gases have been strongly influenced by human activity. The burning of fossil fuels for heat and power is implicated in much of the anthropogenic emissions, but agriculture has also played a role. The opening of the prairies in North America 150 years ago exposed rich deposits of soil carbon to oxidation and, more recently, the widespread burning of rain forests in South America continues to release large quantities of carbon dioxide into the atmosphere. The large stocks of cattle produced today and cultivation of rice are sources of methane and N_2O.

Less certain is the magnitude of global climate change and the urgency for making changes in human activity. The historical and geological records provide only limited information in this regard. Reliable temperature data have only been recorded in very recent times. Various methods for estimating temperature and atmospheric gas concentrations from the geological record suggest a positive correlation between these parameters, but these are subject to considerable interpretation. Increasingly sophisticated computer models are being developed to predict long-term climatic changes, but they remain crude approximations of the real world. Continued research is expected to provide increasingly reliable evidence on how human activity affects global climate.

If society decides to reduce emissions of greenhouse gases, then agriculture will have an important role to play. Agriculture to date has generally been a net emitter of greenhouse gases in the forms of combusted fuels and energy-intensive agricultural inputs such as fertilizer. Agriculture in many developing countries is sometimes a major source of greenhouse gases resulting from direct land-use change. Growth in developing country's populations and the subsequent increased demand for agricultural products has incentivized the conversion of virgin lands for crop production. A common method for the illicit conversion of rainforest and grassland to cropland is the "slash-and-burn" technique, whereby the preexisting biomass on the land is chopped down and burned. While the conversion of rainforests is of particular concern due to the rapid release of the large amounts of CO_2 sequestered in old growth forests and ecosystem destruction, even the conversion of grassland causes emissions due to soil carbon oxidation. Two countries in which rainforest destruction due to direct land-use change has been particularly pronounced are Brazil and Indonesia. Soybean production has increased greatly in Brazil's Amazonian states, as popularized by an image in a 2008 issue of *Time Magazine* showing a rainforest plot surrounded on three sides by soybean fields. Similarly, Indonesia is home to growing production of palm oil, a dietary lipid, which is grown on plantations that have encroached on the country's rainforests. Illegal logging is also blamed for much of the deforestation on the Indonesian island of Borneo.

More recently, concerns have arisen that direct land-use change in the developing world is also being driven by first-generation biofuels production in developed countries. Known as "indirect land-use change" (ILUC), proponents of this effect believe that widespread production of biofuels from crops historically used as food or feed (e.g., corn, soybeans) has created shortages of these crops, causing their prices to increase substantially. Assuming that first-generation biofuel production has caused these price increases, then it is also responsible for at least some of the deforestation that results from slash-and-burn agriculture in rainforest areas.

While ILUC has been discussed since the 1990s, the concept achieved widespread recognition following the publication of a paper in the journal *Science* by Timothy Searchinger and colleagues in 2008 that calculated the lifecycle greenhouse gas emissions of US biofuels when accounting for emissions from ILUC. Specifically, the paper calculated that starch ethanol from corn and cellulosic ethanol from switchgrass emitted 93% and 50% more lifecycle greenhouse gases, respectively, than gasoline. Both biofuels had previously been calculated to have lower greenhouse gas emissions than gasoline without accounting for ILUC emissions, so the Searchinger et al. (2008) paper received immense attention from the US government, academia, and the media.

Subsequent analyses, including one coauthored by most of the original co-authors to the Searchinger paper, found its results to be very sensitive to the assumptions it made. The original analysis was flawed for another important reason; however, it failed to quantify actual rainforest destruction in Brazil during the years in the twenty-first century when US production of ethanol from starch greatly increased. Annual deforestation in the Amazon peaked in 2004 at 2.7 million hectares before falling to 0.5 million hectares in 2012. During the same period, US ethanol production (virtually all of it from corn feedstock) increased from 12 869 million liters to 50 341 million liters. In other words, while the Searchinger analysis predicted that an increase in annual US ethanol production by 56 000 million liters would result in 2 million hectares of tropical deforestation in Brazil alone, the annual rate actually fell by the same number between 2004 and 2012. While it will still only take a few years for 2 million hectares of Amazon deforestation to occur at current rates, the strong negative correlation between US starch ethanol production and rainforest destruction over the last decade suggests that any causal link between the two is tenuous at best.

Much of the decrease in Brazil's deforestation rate has been attributed to the country's enforcement of antideforestation laws, including an expansion of its space program to include the monitoring of Amazonian rainforests via satellite. While the basic mechanism behind the theory of ILUC remains plausible, Brazil's experience with deforestation in the twenty-first century suggests that other factors (such as law enforcement) can override the influence of first-generation biofuel production in the developed world on deforestation in developing countries. Brazil's experience also demonstrates why an accurate quantification of a particular biofuel's lifecycle greenhouse gas emissions under ILUC should consider actual deforestation in the affected country. While the initial greenhouse gas emissions from ILUC attributed to US starch ethanol greatly overestimated the rate of deforestation in Brazil, this will not necessarily be the case for all first-generation biofuels when other tropical countries are considered.

While the greenhouse gas emissions associated with agriculture have been extensively quantified in recent years, negative emissions (also known as carbon sequestration) are also possible. With proper practices, agriculture can not only drastically reduce greenhouse gas emissions but also sequester carbon from the atmosphere. Methane absorbs infrared radiation about 25 times more efficiently than carbon dioxide. Despite its relatively small concentration in the atmosphere, methane is thought to be responsible for 12% of the global warming effect. Thus, one of the most obvious ways for agriculture to reduce greenhouse gas emissions is to divert manure to covered anaerobic digesters where methane can be captured and used for heat and power. Although combustion of 1 mol of methane releases 1 mol of carbon dioxide, no net emission of greenhouse gas to the atmosphere occurs since the manure was derived from plants whose origin was atmospheric carbon dioxide.

Dedicated feedstock supply systems have a unique ability to sequester carbon from the atmosphere. As the plants grow, they absorb carbon dioxide from the atmosphere and convert it into carbohydrates, oils, or proteins. If the aboveground plant material is harvested and used for bioenergy or fuels, carbon dioxide is returned to the atmosphere with no net carbon emissions. If the aboveground plant material is harvested and processed into biomaterials such as plastics or biocomposites, the associated carbon is sequestered for the life of the material, which might be as many as 50 years.

Roots, which are underground biomass, contribute to soil humus, which could be sequestered for centuries. The contribution of roots to sequestered carbon is not trivial; some perennial plants produce almost as much belowground biomass as aboveground biomass. Plantations of SRWC might increase carbon inventories of soil by 30–40 Mg/ha over a period of 20–50 years. Maximum carbon inventories might take a century to be reached.

Char produced by thermochemical processes can be sequestered even longer. Archaeological excavations of pre-Columbian *terra preta* soils in South America suggest that the carbon content of buried char remains sequestered for 1000 years or longer. Applied to agricultural lands as soil amendment and carbon sequestration agent, this carbonaceous residue of gasification and pyrolysis is known as biochar.

11.4 Processing

11.4.1 Heat and Power

The environmental performance of biorenewable resources for the production of heat and power is generally superior to that of fossil resources. Nevertheless, both kinds of resources contain various contaminants that contribute to air pollution when burned. These contaminants include nitrogen, sulfur, chlorine, and, especially for coal and municipal solid waste, heavy metals such as arsenic, cadmium, chromium, lead, and mercury. The concentrations of nitrogen, sulfur, and chlorine for different kinds of fuels are summarized in Table 11.2.

Among the fossil fuels only coal contains significant quantities of nitrogen, sulfur, or chlorine. The relatively small amounts of these contaminants in the raw feedstocks for natural gas and petroleum-derived fuels are substantially removed during the preparation of commercial-grade fuel products (with the exception of

Table 11.2 Concentration of nitrogen, sulfur, and chlorine contaminants in various kinds of fuels

	Nitrogen (wt%)	Sulfur (wt%)	Chlorine (wt%)
Gasoline	–	0.01	–
Bituminous coal	1–2	0.4–3	0.02–0.10
Refuse derived fuel	0.6–0.8	0.3–0.5	0.5–0.6
Woody crops	0.06–0.6	0.01–0.02	0.01–0.10
Herbaceous crops	0.6–1.2	0.01–0.2	0.03–0.6

diesel fuel for stationary power applications, which may contain up to 2.0 wt% of sulfur). Coal also shows the highest concentrations of heavy metals, although diesel oil can contain substantial amounts of vanadium.

Biorenewable resources usually contain less than half the amount of nitrogen as does coal. Wood from traditional lumbering operations may have as little as 0.06% nitrogen although nitrogen-fixing trees such as black locust and heavily fertilized SRWC may contain 10 times this amount of nitrogen. Agricultural residues from heavily fertilized herbaceous crops can contain as much as 1 wt% nitrogen. Biorenewable resources may contain two orders of magnitude less sulfur as coal. On the other hand, biorenewable resources may contain an order of magnitude more chlorine than coal.

Refuse-derived fuel, obtained from municipal solid waste, is a mixture of fossil resource–derived materials, such as plastic, and biorenewable resource-derived materials, such as paper. Accordingly, the amount of nitrogen, sulfur, and chlorine in refuse-derived fuel tends to be intermediate between fossil and biorenewable fuels. Some heavy metals such as cadmium and mercury can be high if care is not taken to remove metal-bearing scrap from municipal solid waste.

The potential environmental impact of processing biorenewable resources to heat and power is illustrated in Figure 11.3. These include formation of acid rain, urban ozone, smog, and PM 2.5. PM 10 arising from ash and soot in flue gas is also a source of air pollution. Incomplete combustion is a source of both VOC (often referred to as unburned hydrocarbons when arising from combustion) and carbon monoxide (CO). Water pollution from inadequate treatment of wastewater can also be a problem.

During combustion, most fuel-bound nitrogen is oxidized to nitric oxide (NO) with smaller amounts of nitrogen dioxide (NO_2) and nitrous oxide (N_2O) also being formed. These nitrogen oxides are collectively designated as NO_x. Gasification and pyrolysis convert fuel-bound nitrogen to ammonia (NH_3) and hydrogen cyanide (HCN). Unless the producer gas is chemically scrubbed, these nitrogen compounds are subsequently oxidized to NO_x when the producer gas is burned.

Based on fuel nitrogen content, coal would appear to be the worst source of NO_x, followed by biorenewable sources, with natural gas and petroleum-based fuels producing only minor amounts of NO_x. In fact, combustion of any type of fuel in air can produce large quantities of NO_x in considerable excess to the amount expected from fuel-bound nitrogen. The reason for this is that nitrogen and oxygen in air can react at high temperatures to produce NO:

$$N_2 + O_2 \leftrightarrow 2NO \tag{11.3}$$

Good combustion practice at one time dictated the use of high temperatures and high excess air (oxygen) levels to assure complete oxidation of carbonaceous fuels. However, these conditions also favor formation of NO. In fact, high levels of NO

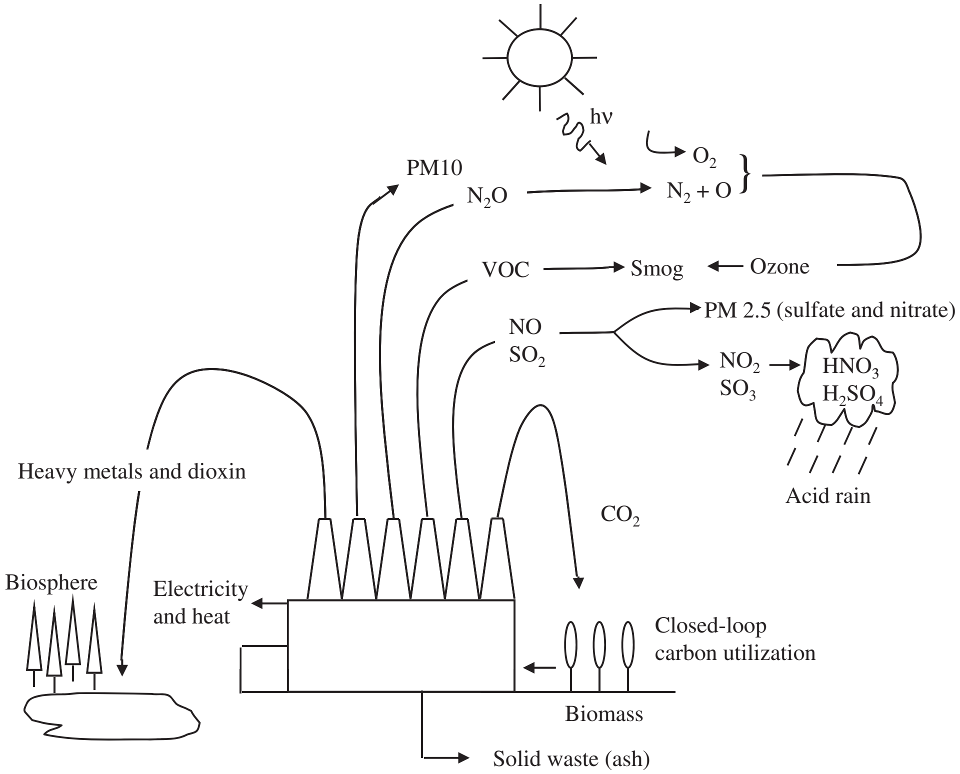

FIG. 11.3 Potential environmental impacts of processing biorenewable resources into heat and power.

in flue gas were once used as an indicator of proper boiler operation. This "thermal NO_x" was the primary source of nitrogen compounds from power plants until environmental regulation in the late twentieth century forced boiler operators to adjust operating conditions to substantially eliminate it. Today, most nitrogen compounds from power plants are "fuel NO_x" and the amount emitted from any given boiler is proportional to the nitrogen content of the fuel. However, even fuel NO_x can be reduced well below the amount expected stoichiometrically by the use of various NO_x control technologies. These include staged combustion and fuel reburning, which exploit oxygen-starved conditions to reduce NO to N_2; selective catalytic reduction (SCR), which injects amine or ammonia into flue gas to react with NO to form N_2; and selective noncatalytic reduction (SNCR), which employs a catalyst to reduce NO. The control of NO_x from liquid fuels, which contain very little fuel-bound nitrogen, is discussed under the section on fuels and chemicals.

Sulfur in fuel is oxidized to sulfur dioxide (SO_2) during combustion or released as hydrogen sulfide (H_2S) during gasification. Unless chemically scrubbed from producer gas, H_2S will be oxidized to SO_2 when the producer gas is burned. Sulfur dioxide is further oxidized in the atmosphere to form sulfuric acid, which can form acidic water droplets or sulfate aerosols. Thus, both nitrogen oxides and sulfur dioxide contribute to the formation of acid rain and PM 2.5. Sulfur dioxide is not implicated in urban ozone or smog.

Sulfur emissions from coal-fired power plants can be controlled by reaction of metal oxide sorbents, such as CaO derived from limestone, with either SO_2 in flue gas or H_2S in producer gas. Hydrogen sulfide can also be removed by reaction with aqueous amine solutions. Biorenewable resources, which typically only contain 0.01 wt% sulfur, do not require emission controls to meet regulations on sulfur dioxide.

Fuel chlorine is converted to hydrogen chloride (HCl) during combustion, which forms hydrochloric acid upon reaction with water droplets. Hydrogen chloride, along with the oxides of nitrogen and sulfur, is known as acid gas. Unlike the other acid gases, HCl has not been implicated in formation of acid rain or PM 2.5. Because it reacts so readily with water, acid will form once flue gas drops below the dew point of the mixture of water and HCl. This usually occurs within the plant, where it can corrode equipment. Only a few fuels have sufficiently high chlorine for this to be a problem: refuse-derived fuel because of certain kinds of plastics and a few agricultural residues like wheat straw and corn stover. In these cases, scrubbing HCl from the flue gas is important to prevent equipment corrosion.

A more insidious effect arising from fuel chlorine is the formation of dioxin in combustion equipment. Dioxin refers to 210 compounds—75 dioxins and 135 furans—with similar structures and properties. Only 17 of the 210 compounds are toxic, and these differ considerably in their potency. Some of these are animal carcinogens or have been implicated in birth defects. Combustion-generated dioxin is thought to arise primarily from solid-phase reactions involving metal chlorides and fly ash carbon, which chlorinates aromatic hydrocarbons to produce dioxins. Ironically, high levels of sulfur in flue gas short-circuit the reactions that produce dioxin. For this reason, combustion of refuse-derived fuel, which contains a relatively low ratio of sulfur to chlorine, can generate high dioxin emissions, whereas combustion of coal, which typically has high sulfur-to-chlorine ratios, has not been implicated in dioxin emissions. Examination of Table 11.2 suggests that many herbaceous crops would also generate dioxin unless cofired with coal. The oxygen-starved conditions of gasification do not produce dioxins.

Incomplete combustion generates VOC and carbon monoxide (CO). Efforts to reduce NO_x emissions based on staged combustion exacerbate the emission of VOC and CO since they form under fuel-rich conditions. Any fuel, whether derived from fossil resources or biorenewable resources, can emit VOC and CO upon combustion. As previously noted, VOC plays a role in smog formation while CO contributes to cardiovascular disease. Combustion control, including adjustment of flame position within the boiler and addition of secondary air to complete combustion, usually can achieve satisfactory levels of these products of incomplete combustion.

Heavy metals released from fuels upon combustion typically form oxides or chlorides that exist as particulate, although elemental mercury also has been detected as vapor in flue gas. The particulate is apportioned between bottom ash, which collects below the grate of certain kinds of boilers, and fly ash, most of which is captured by particulate-control devices, although some escapes into the atmosphere with the flue gas. Coal contains on the order of one-tenth of a part per million of various heavy metals while biomass crops grown on uncontaminated soil contain virtually none. Although heavy metals are present in only trace quantities, they are highly toxic and some, like mercury, are "bioaccumulators"; that is, they are taken up by plant or animal tissue and can move through the food chain where they accumulate to toxic concentrations in higher life forms. Proposals to regulate heavy metal emissions increase the attractiveness of biomass in the production of power.

When burned, solid fuels and heavy fuel oils, whether derived from fossil resources or biorenewable resources, emit primary PM in the form of ash and soot. Uncontrolled emission of these particles into the atmosphere was the most visible manifestation of air pollution before the introduction of particulate control devices. Cyclones, electrostatic precipitators, and baghouses are effective in reducing primary PM. Early regulation focused on PM finer than 10-μm size (PM 10), the most difficult fraction of primary PM to capture within the plant. More recent regulation focuses on PM 2.5, which is chiefly secondary particulate formed outside the plant, since it is considered the more serious health risk.

Properly managed heat and power production results in very little water pollution regardless of the fuel source. Wastewater is generated if fuel is cleaned before it is burned or if spray towers are used to scrub out dust, tar, or other pollutants from producer gas or flue gas. This wastewater can be a significant source of pollution if not properly handled. Indeed, many of today's federal Superfund cleanup sites are the legacy of widespread coal gasification at the turn of the century to produce "town gas" for lighting and heating. Tar in the producer gas from these early gasifiers was removed by scrubbing the gas stream with water, which was disposed of in holding ponds where the tar contaminated the soil. However, modern wastewater treatment technology is able to produce an effluent that does not contaminate the environment.

Production of heat and power is a significant contributor to greenhouse gas accumulation in the atmosphere, including nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2). Although water, produced by the combustion of hydrogen-bearing fuels, is also a greenhouse gas, anthropogenic activity is not thought to substantially affect the cycling of water between the Earth's surface and the atmosphere. Nitrous oxide, although a powerful absorber of infrared radiation, can be substantially eliminated by careful combustion control. Methane is not intentionally emitted into the atmosphere, although leaks from natural gas distribution systems can be significant if not carefully managed. The most difficult greenhouse gas to manage in the production of heat and power is carbon dioxide from the burning of carbon-bearing fuels, which includes both fossil resources and biorenewable resources. However, since biorenewable resources obtain their carbon by extracting carbon dioxide from the atmosphere, essentially no net emissions of carbon dioxide result from growing and burning biorenewable resources. The accounting of net carbon dioxide emissions is somewhat complicated by the fact that agricultural production currently employs fossil fuels to power tractors and manufacture fertilizer; however, this contribution is small and is expected to diminish as biorenewable resources are increasingly used for production of transportation fuels and chemicals.

11.4.2 Chemicals and Transportation Fuels

Processing of biorenewable resources to chemicals and transportation fuels, illustrated in Figure 11.4, can be a significant source of pollution of air, water, and soil, depending on the processes involved and the management of byproducts. Because of the diversity of these processes and byproducts, it is not possible to provide a comprehensive evaluation of their environmental impacts. Instead, the wet corn milling process will be used to illustrate the kinds of pollution problems that must be addressed in the production of chemicals and fuels.

Emission of PM is a major problem in grain handling and storage operations at a corn wet milling plant. These emissions arise from mechanical energy imparted on the corn during conveyance and can be reduced by minimizing grain free fall distances and grain transport velocities within the plant and by sealing grain receiving areas and process equipment. However, generation of some dust is inevitable, which can require ventilation systems operated in conjunction with cyclones or baghouses to control fugitive dust emissions.

The corn steep operation in wet milling plants uses 1.1–2.0 kg of SO_2 per megagram of corn. The pungent odor of SO_2 in process water dictates the enclosure and venting of process equipment. Vents can be wet-scrubbed with alkaline solution to remove SO_2 from the exhaust gas.

The most objectionable emissions from corn wet milling plants are VOC released from drying processes. In particular, drying of distillers' dried grains yields VOC with a variety of odors: acetic acid and acetaldehyde produce acrid odors; butyric acid and valeric acid yield rancid odors; and aldehydes produce fruity odors. Moderating drying temperatures can reduce the resulting blue haze from these driers. Further control is achieved with ionizing wet collectors or thermal oxidation of drier vent gases at 750°C for at least 0.5 seconds.

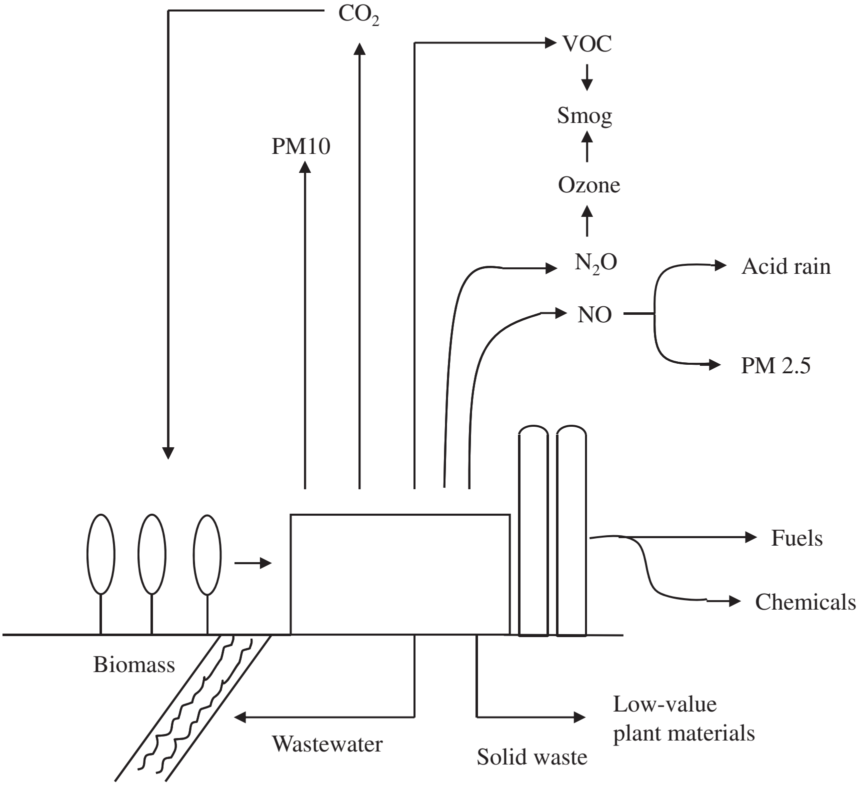

FIG. 11.4 Potential environmental impacts of processing biorenewable resources to chemicals and fuels.

If the starch product from a corn wet milling plant is used to produce ethanol as transportation fuel, two other environmental concerns are raised. The first is whether production of ethanol from corn reduces reliance on fossil fuels. Some studies have suggested that more energy is consumed in producing the grain (in the form of nitrogen fertilizer and fuel for agricultural equipment) and converting it to ethanol (especially during the energy-intensive distillation processes) than appears in the final fuel product. At the very least, it is clear that current corn-to-ethanol production and processing systems rely heavily on fossil fuels, a situation that should be addressed if ethanol is to become a major transportation fuel. Closely related to this issue is the net emission of greenhouse gases from the production of ethanol fuel from corn. Although carbon cycles from the atmosphere to the corn crop, into the ethanol product, and back to the atmosphere upon combustion as transportation fuel, the fossil fuels used in production of fertilizer, operation of tractors and combines, and distillation of ethanol contribute toward a net positive increase in carbon dioxide to the atmosphere. To rectify this situation, future biomass-to-ethanol production should reduce the use of fossil fuels or switch to those with lower greenhouse gas emissions, such as natural gas.

Modern corn milling plants produce few water pollution or solid waste disposal problems. Wet corn milling operations produce wastewater that requires treatment. Aeration ponds are used to oxidize SO_2 to sulfate, which precipitates out into settling ponds. Corn milling produces low-value byproduct streams in the form of corn fiber from wet milling and distillers' dried grains and solubles (DDGS) from dry milling. Despite their low value, these byproducts find application as feed additives. However, if ethanol production were significantly ramped up to provide transportation fuels, these byproducts would be in excess supply and might represent a solid waste disposal problem. Landfilling of byproduct streams is already a problem in the manufacture of high-value chemicals like plant enzymes.

Cellulosic biofuel pathways avoid the issues of carbon and energy intensity by relying on a fraction of the biomass feedstock for facility power. Frequently this fraction is a low-value pathway coproduct such as separated lignin or noncondensable gases (NCG). The lifecycle GHG emissions of cellulosic biofuels are estimated to be much lower than starch ethanol as a result. Cellulosic biorefineries can still have negative impacts on the local environment, however. Like starch ethanol, cellulosic ethanol production produces a wastewater stream that must be treated prior to disposal. Excessive removal of agricultural residue feedstocks such as corn stover contributes to soil erosion from wind and water, effects that can be mitigated by leaving one-third or more of the stover produced per acre on the cropland. Finally, benzene, a carcinogen, is among the hydrocarbons produced via drop-in cellulosic biofuel pathways. Precautions must be taken during handling and distribution as a result.

11.4.3 Fibers

The early history of the pulp and paper industry demonstrates that use of biorenewable resources is not inherently environmentally benign. The notorious "papertown smell" around pulp and paper mills came from reduced sulfur compounds, corrosive and malodorous gases arising from the use of sulfur chemicals in the pulping process. Furthermore, spent liquor discharges from paper mills turned the waters of local streams black and barren of aquatic life. In the latter half of the twentieth century, process improvements have substantially reduced these early problems, although concerns about environmental performance remain, as illustrated in Figure 11.5.

Of the two major chemical pulping processes, the sulfite process was originally preferred because of its ability to produce a lighter, easier-to-bleach pulp compared to the sulfate (kraft) process. Increasing environmental regulation gradually shifted

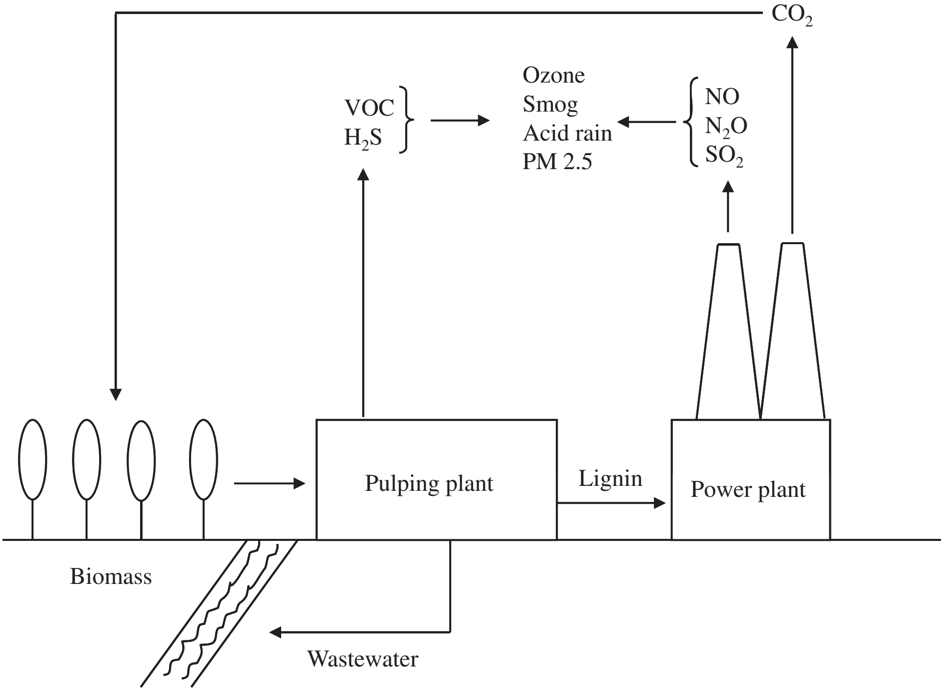

FIG. 11.5 Potential environmental impacts of processing biorenewable resources into fibers.

the industry toward the kraft process because of its ability to more economically recover chemicals from spent liquor, thus avoiding its discharge into rivers.

However, the kraft process, which requires extensive bleaching to produce white paper, introduced another environmental problem. The most economical bleaching compound is elemental chlorine (Cl_2), which reacts with organic compounds in the spent liquor to form "adsorbable" organic halogens (AOX), including dioxins and furans, some of which are very toxic to humans and animal life. Many of these organic halogens, discharged to rivers and bays, have found their way into food chains. This problem is being addressed by the adoption of elemental chlorine-free (ECF) technology, which uses chlorine dioxide, and totally chlorine-free (TCF) technology, which is based on various combinations of hydrogen peroxide, oxygen, chelating agents, and ozone treatment.

Wastewater contains cellulose fibers, polysaccharides, and various organic and inorganic compounds. Wastewaters are discharged at a rate of 20–250 cubic meters per metric ton (m^3/t) of air-dried pulp (ADP). They are high in biochemical oxygen demand (BOD), at 10–40 kg/t of ADP; total suspended solids, 10–50 kg/t of ADP; chemical oxygen demand (COD), 20–200 kg/t of ADP; and chlorinated organic

Table 11.3 Range of pollution emissions (kg/t of ADP[a]) from pulp and paper mill using the kraft process

Reduced sulfur	VOCs	Sulfur oxides	Nitrogen oxides	Particulate matter
0.3–3	15	0.5-30	1–3	75-150

Source: World Bank Group (1998) Pulp & paper mills. In: *Pollution Prevention and Abatement Handbook*. World Bank. [a]Air-dried pulp.

compounds, which may include dioxins, furans, and other adsorbable organic halides, at 0–4 kg/t of ADP.

Primary treatment is performed with a mechanical clarifier or settling pond to recover cellulose fibers, which are recycled. Chemical precipitation is used to remove certain cations. Secondary treatment is performed in aerated lagoons or anaerobic fermenters to reduce BOD by over 99%. Tertiary treatment may be performed to reduce toxicity, suspended solids, and color.

The kraft process also contributes to air emission problems. Reduced sulfur compounds, measured as total reduced sulfur, emitted to the atmosphere from the pulping process include hydrogen sulfide, methyl mercaptan, dimethyl sulfide, and dimethyl disulfide. Volatile organic compounds are emitted during the concentration of black liquor in multiple-effect evaporators. Acid-precipitated lignin from the concentrated black liquor is used as boiler fuel. The remaining pollution emissions, sulfur oxides, nitrogen oxides, and PM, arise from combustion of the lignin. Table 11.3 lists the range of pollution emissions from pulp and paper mills operating on the kraft process. Emissions are reported as kilograms of pollutant per ton of ADP, which contains 10 wt% water.

11.5 Utilization

We have seen that production of biorenewable resources and their processing into biobased products can generate pollutants with adverse impacts on the natural environment. The final products themselves can also have adverse environmental impacts, either in the way they are used or in how they are disposed of at the end of their useful lives. Sometimes these impacts are not obvious until the product has been commercially introduced and its effects on the environment are monitored. Such an approach is not viable if these impacts are potentially large and negative. For this reason, lifecycle analysis, which attempts to anticipate the environmental impact of a new product from its manufacture to its final disposal, is increasingly performed before introducing a new product.

Among the most scrutinized biobased products in the United States is fuel ethanol from corn. Its environmental advantages compared to gasoline, including its ability to reduce GHG emissions and tailpipe pollutants, have been widely touted. However, careful scrutiny reveals that environmental advantages are much harder to justify.

Fuels that contain oxygen, so called oxygenates, are reported to be more "clean-burning" than hydrocarbon fuels since complete combustion is promoted by high oxygen content of the air–fuel mixture. In principle, ethanol, which contains 35 molar% oxygen, should reduce emissions of carbon monoxide, PM, and VOC. For this reason, the US Clean Air Act Amendments of 1990 mandated the use of gasoline containing oxygenates, called reformulated gasoline, to be sold in urban areas that did not meet national targets for reducing urban ozone. The two most commonly employed oxygenates to meet this regulation were methyl tertiary butyl ether (MTBE) and ethanol. MTBE is now banned as a fuel oxygenate in some parts of the world because this toxic compound has become a serious water pollution threat.

Vehicle testing reveals that ethanol is effective in reducing carbon monoxide emissions from the carbureted engines that were in wide use when ethanol was introduced in the 1970s. However, modern automobiles employing computer-controlled, fuel-injected engines are able to achieve near-complete combustion independent of the oxygen content of the fuel, leading some critics to claim that reformulated gasoline is obsolete. The effect of ethanol on emissions of PM is not well documented.

The actual effect of ethanol on VOC emissions illustrates the importance of life-cycle analysis for new products that potentially have large environmental impacts. The marginal impact of ethanol on CO emissions from modern internal combustion engines might also be expected to be true in the case of VOC emissions, another product of incomplete combustion. In fact, there is evidence that reformulated gasoline based on ethanol exacerbates VOC emissions from automobiles as a result of increased fuel volatility: although tail pipe emissions of VOC might decrease marginally, fuel tank emissions increase significantly, from 34% of total VOC emissions from conventional gasoline to 42% of total VOC emissions from gasoline reformulated with ethanol. Evaporative emissions from fuel tanks are a direct function of fuel vapor pressure. Neat ethanol and high-level ethanol blends with gasoline have lower vapor pressures than gasoline; however, vapor pressure increases as the percentage of ethanol decreases. Reformulated gasoline, which employs only 10% ethanol, has a higher vapor pressure than conventional gasoline, thus explaining the higher VOC emissions from the ethanol blends commercially available in the United States. Blending 10% ethanol with 90% gasoline increases the fuel volatility (measured in Reid Vapor Pressure (RVP)) over that of conventional gasoline by 3.4–6.9 kPa. A possible solution to this problem is the use of ethyl tertiary butyl ether (ETBE), which does not produce this confounding effect.

Oxygenated fuels may affect NO_x emissions. Although ethanol contains no nitrogen, high oxygen levels promote thermal NO_x formation. On the other hand, the lower flame temperature for combustion of ethanol should favor lower thermal NO_x formation. Engine testing has produced inconsistent results, but some environmentalists argue that ethanol-fueled automobiles exacerbate NO_x emissions.

Biodiesel, which is produced via transesterification of lipids, has also been found to reduce tailpipe particulate and hydrocarbon emissions relative to diesel fuel. While biodiesel does increase NO_x emissions, renewable diesel produced via hydroprocessing of lipids reduces these relative to diesel fuel as well.

Among the most attractive benefits of using ethanol fuel is reducing GHG emissions. Since the carbon in ethanol comes from plant material, the argument is that ethanol produces no net carbon dioxide emissions: an amount of carbon dioxide equivalent to that released during combustion of ethanol, which is taken up by crops, will be processed into additional ethanol. This is a potentially important role since conventional transportation fuels account for 28% of anthropogenic carbon dioxide emissions in the United States. Lifecycle analysis reveals the flaw in this argument: the current system of converting corn starch to ethanol in the United States consumes large quantities of fossil fuels that must be included in the accounting of net carbon dioxide emissions. Farm machinery is fueled by gasoline produced from petroleum. Nitrogen fertilizer is manufactured in an energy-intensive process from natural gas. Distillation of ethanol requires large quantities of energy obtained from coal or natural gas.

The range of net carbon dioxide emissions has been estimated at 15–71 kg/GJ, depending on the assumptions made for fuel source and fuel energy requirements for the conversion of corn to ethanol, how byproducts are treated, and how ILUC is accounted for. In contrast, gasoline has a net emission rate of about 76 kg/GJ. Thus, some critics claim that the superiority of corn ethanol compared to gasoline in fighting global climate change is marginal or, if a high ILUC factor is employed, nonexistent. On the other hand, ethanol produced from lignocellulosic materials has lower energy inputs during production, and all process energy comes from feedstock byproducts. Net carbon dioxide emission rates are expected to be only 8–15 kg/GJ from cellulosic biofuel production and conversion systems. Negative emission rates (i.e., net sequestration) can even be achieved by pathways such as pyrolysis when a large amount of char is produced and sequestered.

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