CHAPTER

5

Production of Biorenewable Resources

5.1 Introduction

Biomass is produced through the practice of agriculture, silviculture, and aquaculture. Traditionally, agriculture was considered the cultivation of herbaceous plants primarily for food and animal feed; silviculture, the maintenance of forests, usually on timescales of decades, either for commercial, recreational, or ecological purposes; and aquaculture, the cultivation of marine or freshwater food sources, usually fish or shellfish. None of these terms fully encompasses the activity of cultivating autotrophic life forms as a means of harvesting solar energy for the production of fuels, chemicals, materials, and energy. Commonly the growth and harvesting of terrestrial vascular plants, whether herbaceous, woody, or oleaginous species, is referred to as agriculture, while growth and harvesting of aquatic non-vascular species such as microalgae will be referred to as aquaculture. Productions of herbaceous crops and woody crops are treated in separate sections of this chapter because of the different timescales associated with their cultivation and the different approaches to their mechanized harvest. Production of oleaginous crops focuses on microalgae rather than oil seed crops, because the later closely follows the production of herbaceous crops. This chapter also considers the storage of biorenewable resources and the application of biotechnology to the production of transgenic crops.

5.2 Herbaceous Crops

As described in Chapter 4, herbaceous crops are plants that have little or no woody tissue and the above-ground growth usually lives for only a single growing season. These include annuals, which die at the end of a growing season and must

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be replanted from seed, and perennials, which die back each year in temperate climates but reestablish themselves each spring from rootstock.

Broadly defined, herbaceous crops include grasses, such as switchgrass, sugar cane, and cereals like corn and wheat; pulses, which are the leguminous plants, such as soybeans, lentil, and alfalfa; and tubers, including potatoes, taro, and Jerusalem artichokes. All have potential application as part of dedicated feedstock supply systems. However, most development has centered on grasses, which is also the focus of this chapter.

5.2.1 Site Preparation

Preparation of the growth zone in soil for plant development is known as tillage. Typically, this tillage zone extends 10–90 cm into the soil. The depth of organic matter in the soil defines the tillable zone. Tillage is required in virgin soils to clear it of plant matter for agricultural use. It also may be performed as part of the process of transferring seeds or seedlings into the soil in a manner conducive to healthy growth of the plants. Ideally, the seed bed is stratified, consisting of a base of coarsely loosened soil, a root development zone of porosity conducive to capillary movement of water, a seed bed zone of fine soil to surround the seeds, and an upper zone of small clods to protect the seeds, as illustrated in Figure 5.1. Tillage is also used to control weeds and other pests living in the soil, although chemical means of pest control have largely supplanted mechanical methods of control.

Texture is a way to classify different sizes of particles making up soil. These classifications include clay (particles smaller than 0.002 mm), silt (particles between 0.002 and 0.05 mm), sand (particles between 0.05 and 2 mm), and gravel and cobbles (particles larger than 2 mm). The latter particles are undesirable as they interfere with tillage and retain little organic matter.

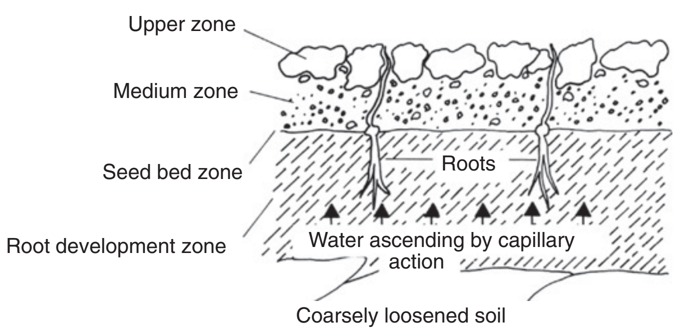


FIG. 5.1 Stratified seed bed of properly tilled soil. Adapted from *CIGR Handbook of Agriculture Engineering, Vol. III: Plant Production Engineering*, B.A. Stout and B. Cheze, eds. St. Joseph, Mich.: American Society of Agricultural Engineers, 1999.

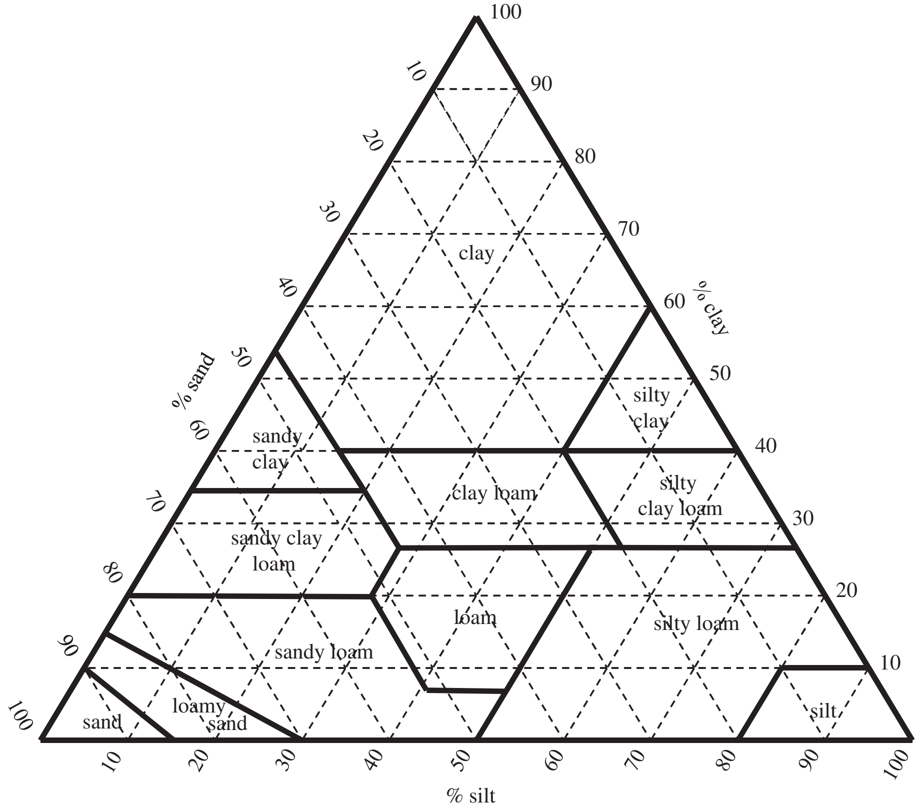


FIG. 5.2 Soil classification triangle. Adapted from *CIGR Handbook of Agriculture Engineering, Vol. III: Plant Production Engineering*, B.A. Stout and B. Cheze, eds. St. Joseph, Mich.: American Society of Agricultural Engineers, 1999.

Soils are classified according to the distribution of the first three size classes (clay, silt, and sand). Soil classifications are represented by the texture triangle shown in Figure 5.2. Soil type greatly influences its workability and suitability for agriculture.

Sands and sand soils, also known as light soils and shown on the lower left hand corner of the texture triangle, are easy to work at all moisture levels. However, water storage capacity is low while infiltration rate and water conductivity are high. This is an advantage for irrigated soils, as salt does not accumulate. Crop yields for sand soils are lower than other types of soils, because organic matter and nutrients are not readily retained.

Silty and loamy soils, also known as medium soils and shown on the lower right hand corner of the texture triangle, are the best agricultural soils. They readily retain water and have porosity suitable for good aeration. They readily retain organic matter and minerals required for good plant growth.

Clay soils, also known as heavy soils and shown on the upper corner of the texture triangle, are difficult to cultivate. At low moisture content they become hard, rendering tillage very difficult. At high moisture content they become plastic, which makes crumbling almost impossible and requires very high draft forces for tillage implements. Porosity is high, but the pores are so fine that aeration is poor and the contained water is inaccessible to plants.

One of the main objectives of tillage is achieving soil porosity that is conducive to both soil aeration and water accessibility to plants. An optimum tilth is usually obtained when crumbs are smaller than 50 mm and a sufficient number of clods exist to create porosity and protect the land against erosion. In the absence of clods, crumbs are readily broken up by wind and water into silty particles that form surface encrustations upon exposure to water. These encrustations interfere with plant growth. In humid climates, looser soil conditioning helps prevent encrustation and improves aeration. In dry climates denser soil conditioning improves water retention.

Figure 5.3 illustrates three types of tillage systems: conventional tillage, reduced tillage, and no-till. The practice of conventional tillage, characterized by high intensity of soil engagement and inversion of the soil, has rapidly declined in the last 50 years because of concerns about soil erosion. Reduced tillage encompasses a wide variety of cultivating practices that have in common less frequent and less intense tillage of the soil compared to conventional tillage. No-till, made possible

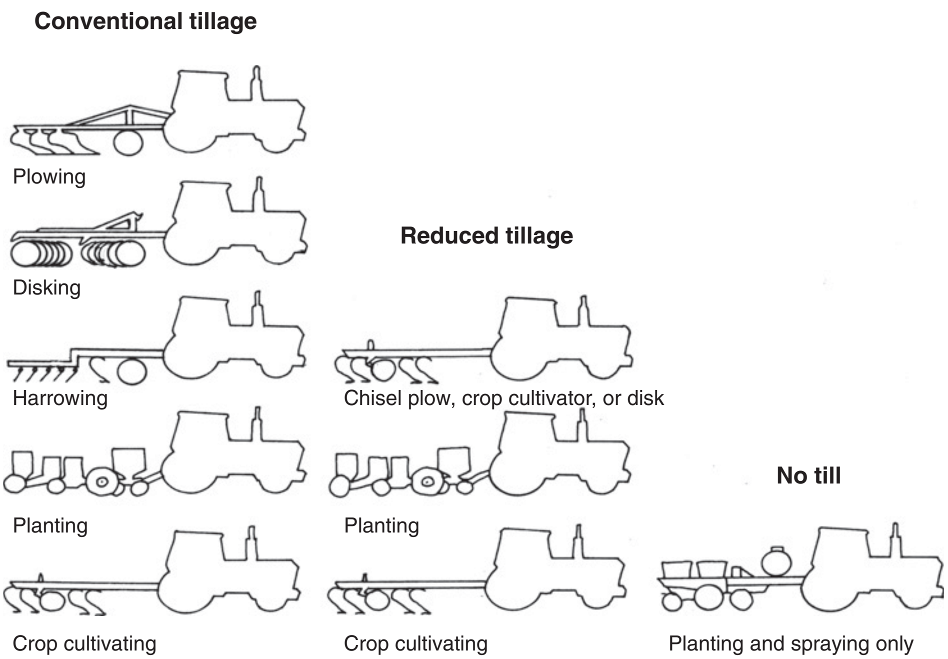


FIG. 5.3 Tillage methods.

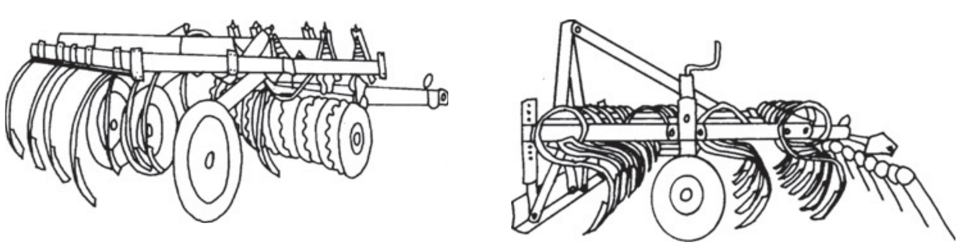
by the development of chemical herbicides, entails very little disturbance of the soil in planting a crop.

Conventional tillage consists of primary tillage followed by several operations of secondary tillage. In heavy soils, primary tillage is accomplished with a moldboard plow. The soil is cut horizontally by a sharp steel element known as a share, and lifted and turned over by a large planar surface known as the moldboard. In arid climates a disk plow is employed, which is less susceptible to obstacles and rough conditions. However, the disk plow is less effective at inverting and crumbling high-organic soils than is the moldboard plow. Primary tillage buries both weeds and plant residues from the previous year's crop. It also produces relatively large soil aggregates; thus, it must be followed by secondary tillage to create a fine seedbed. Among the most common secondary tillage implements is the disk harrow, commonly called a "disk," consisting of several sets of disks on a horizontal axis, angled toward the direction of travel. Dragged over a plowed field, it crumbles, loosens, mixes, and levels the soil into a seedbed. A spiked-tooth harrow, resembling a garden rake in its action, is another implement of secondary tillage.

Reduced tillage is designed to reduce the number of steps in cultivating the soil, with corresponding savings in labor and energy inputs. Some forms of reduced tillage also constitute conservation tillage, which is defined as tillage practices that retain at least 30% of plant residue from the previous year's crop on the surface of the soil. This residue discourages movement of soil by wind and water erosion. Although several different methods of reduced tillage are practiced in different regions of the world, they generally do not employ moldboard or disk plows.

One system of reduced tillage is based on one or two passes of a disk harrow over a field followed by seeding. The greater the disk angle, the greater the degree of soil disturbance and the greater the amount of crop residue that is buried. Generally, not enough residue remains on the soil surface for this method to qualify as conservation tillage.

Another system employs one or two passes of a chisel plow, illustrated in Figure 5.4a. Disk-shaped blades, known as coulters, at the front of the implement cut crop residues, preventing it from plugging the rows of chisels at the back of the



(a) (b)

Fig. 5.4 Reduced tillage implements: (a) stubble mulch chisel plow; (b) spring-tined cultivator.

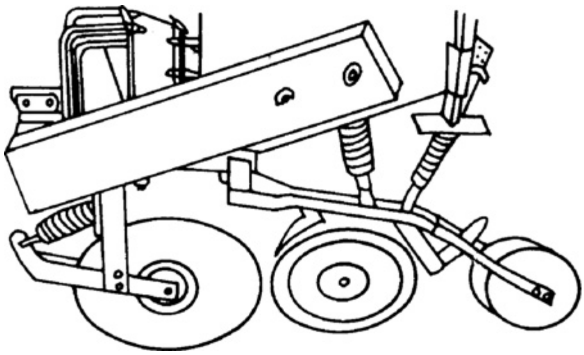


Fig. 5.5 Zero till planter.

implement. The chisel plow cuts the soil to depths of 15–20 cm without burying the entire crop residue. Typically, more than 30% of the residue remains on the soil surface, thus qualifying as conservation tillage. Alternatively, a field cultivator, illustrated in Figure 5.4b, is used in place of the chisel plow or for the second pass over the field after use of the chisel plow. The field cultivator does not cut the soil as deeply as a chisel plow, which helps conserve soil moisture, but it is not as effective in reducing weeds.

Zero or no tillage plants seeds directly into essentially unprepared soil. A typical machine for no till is illustrated in Figure 5.5. This machine cuts a line in the soil for insertion of seeds but does not otherwise disturb the soil. Its success is premised on the use of herbicides to kill weeds before planting.

5.2.2 Seeding and Planting

The final step in planting is insertion of seeds, seedlings, or vegetative propagations into the prepared soil. The term "planter" is used to describe machines that insert seeds into the soil as well as to machines designed for planting seedlings or vegetative propagations.

A simple system of metering a stream of seeds from a hopper through a feeder tube into a furrow is known as bulk drilling and is commonly employed for closely spaced crops such as small grains and grasses. In contrast, widely spaced crops, such as corn and soybeans, are planted using precision drilling, which aims at equidistant spacing of seeds. A modern planter designed to separate seeds for precision drilling is illustrated in Figure 5.6. Drilling depth depends on seed size and water content of the soil: the larger the seeds and the drier the soil, the deeper the seeds are planted to ensure emergence.

The planting of parts of plants, such as potato tubers, and whole plants, such as trees, has also been mechanized. As might be expected, the machines for vegetative

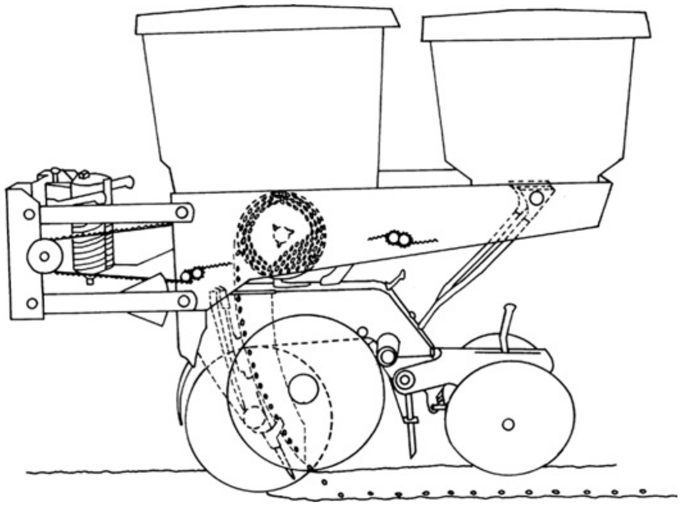


Fig. 5.6 Precision seed drill. Courtesy of Deere and Company.

planting are more complicated than seed planting, and they are designed for specific kinds of plants.

5.2.3 Fertilizer Application

Natural soil fertility declines with crop production, because a large fraction of the biomass is removed from the land, taking with it essential nutrients. Fertilizer is a natural or manufactured material containing high levels of nutrients essential to plant growth. The major nutrients are nitrogen (N), in the form of nitrate, ammonia, or urea; phosphorous (P), analyzed in terms of the P_2O_5; potassium (K), analyzed in terms of K_2O; and calcium (Ca), analyzed in terms of CaO. Although fertilizer requirements vary with soil type and climate, estimated application rates for several biomass crops are listed in Table 5.1.

Fertilizer spreaders are designed for uniform distribution of powdered, granular, or liquid fertilizer, which is critical for optimum performance: either excessive or inadequate application of chemical will reduce crop yield.

A number of distributor types have been developed for powdered and granular fertilizer, including spinning disk spreaders, oscillating spout spreaders, pneumatic spreaders, and auger spreaders. The spinning disk spreaders consist of a conical hopper feeding a spinning disk that is fitted with several radially oriented vanes. Fertilizer falling onto the disks is directed outward along the vanes at velocities of 15–50 m/s, which yields a large broadcast area for the fertilizer. Oscillating spout spreaders consist of a mechanically agitated hopper connected to a spout that vibrates in the horizontal plane. Fertilizer granules are accelerated by the

Table 5.1 Estimated fertilizer requirements for selected crops

	Required Mass Per Unit Weight of Whole Dry Plant, kg/dry ton			
Biomass	N	P_2O_5	K_20	CaO
Alfalfa	0	12.3	34.0	20.7
Corn	11.8	5.7	10.0	0
Kenaf	13.9	5.0	10.0	16.1
Napier grass	9.6	9.3	15.8	8.5
Slash pine (5 year)	3.8	0.9	1.6	2.3
Potato	16.8	5.3	28.3	0
Sugar beet	18.0	5.4	31.2	6.1
Sycamore	7.3	2.8	4.7	0
Wheat	12.9	5.3	8.4	0

Source: Roller, W.L., *et al.* (1975) Grown organic matter as a fuel raw material resource. *NASA Report CR-2608*. Washington, DC: National Aeronautics and Space Administration.

centrifugal forces in the spout, bouncing along the wall a couple of times before being discharged. Pneumatic spreaders entrain granules in a fast-flowing air stream. The air transports the fertilizer through long tubes supported by booms. Deflector plates at the end of the tubes spread the suspension into fans, which provide uniform coverage over the field. Auger spreaders deliver fertilizer from a hopper by means of scrapper floor chains or rubber auger belts to spreading auger booms. They are preferred for application of dusty soil ameliorants, such as potash or ground lime, at high rates.

Liquid fertilizers are of three types: anhydrous ammonia, solution fertilizers, and suspension fertilizers. Although technically more difficult to apply, they have several advantages compared to granular fertilizers including more effective application and the ability to combine fertilizer application with pest control. Because of its high vapor pressure, anhydrous ammonia is injected directly into the soil to prevent its dispersion into the atmosphere. Solution fertilizers consist of soluble fertilizers in water, such as ammonia, urea, or ammonium nitrate. Suspension fertilizers employ a gelling type of clay as an emulsifier to keep finely divided particles of fertilizer in suspension, which is an effective method for applying potassium fertilizer. Both solution and suspension fertilizers can be applied with field sprayers. Directing liquid over spinning fans forms coarse sprays suitable for application to the soil. Liquid nozzles form fine sprays suitable for direct application to plant leaves.

5.2.4 Pest Control

During the growing season, pest control may be required. Pests are anything that impedes or competes with the desired crop and may include weeds, insects, or disease. Control includes mechanical, chemical, and biological methods as well as combinations of these methods known as integrated pest management.

Mechanical weeding removes competing plants from the soil. A number of machines have been developed to support weeding in mechanized farming. The hoeing machine consists of tines or rotary hoes that uproot weeds between rows to a soil depth of 5 cm. The treatment is effective on dry, compact soil and is usually combined with banding application of herbicides. Blade cultivators cut weed roots and rhizomes to a depth of 10 cm by means of horizontal blades mounted on shanks. Brushing machines, effective during early weed emergence, are sets of rotating brushes that uproot weeds between the rows. Chain harrows consist of sets of narrow, flexible, vertical steel spikes that scratch the soil and root out post-emergent weeds from pre-emergent crop or shallow-rooted weeds from amongst deep-rooted crops. The harrow is particularly suited to non-row crops.

Chemical pest control was extensively developed after World War II and is currently the dominant method of controlling weeds, insects, and diseases in crops. Chemical control is classified as either contact or systemic. Contact methods are dependent on local action of the chemical at the point of application, whereas systemic methods are based on absorption and transport of chemicals through the plant to the point of action. The active ingredients of chemical pest control are classified as herbicides, which act against weeds; insecticides, which act against insects; or fungicides, which act against fungi. Dry applications are used where water is scarce or for certain compounds for which powders are more effectively deployed than liquid sprays. Spray applications can be very effective under appropriate meteorological conditions. For example, wind speeds should be below 3 m/s to avoid spray drift, temperature above 10°C promotes leaf absorption, and slight rain or dew improves efficacy of chemical deposition on plant surfaces. A variety of sprayers have been developed including broadcast sprayers, directed or banded sprayers, and in-furrow sprayers.

Biological pest control is of growing interest as a means of reducing the sometimes unfavorable environmental impact of chemical pest control. In this method, fields are deliberately infested with predators and parasites of the pest. The eggs, larvae, or adults of pest predators are mixed with inactive material such as sawdust or hulls and distributed manually by workers walking through the fields to be treated. Because of the multiplier effect of biological pest control (one predator can often consume multiple pests), application rates of the mixtures are low, usually in the range of 5–30 L/ha.

5.2.5 Harvesting

Harvesting is the process of gathering a mature crop from the field. Specific machines have been developed for handling different types of crops: cereals, forage, canes, fruits, nuts, and vegetables. Some of these machines are also able to separate the desired agricultural product from residual plant material (e.g., separating corn kernels from cob, husk, stem, and stalk). In the case of grain crops, this separation process is known as threshing. A machine that combines both harvesting and threshing of grain crops (cereals) is known as a combine harvester (or simply combine). Since grains and seeds, forage crops, and canes are the agricultural crops of particular interest as feedstocks for biobased products, only harvesting methods appropriate to these three crops will be discussed.

Grain Harvesting

Combine harvesters can harvest a wide variety of grains and seeds, ranging from mustard seeds to broad beans. Combined losses of grain from cutting, threshing, and cleaning can be as low as 1–3%. Mechanical methods have increased productivity of grain harvesting from as little as 10 kg/man-hour in 1800 to 60 000 kg/man-hour today.

The major subsystems of a combine harvester include the gathering and cutting unit (head), the threshing unit, and the cleaning unit. Different kinds of gathering and cutting units are used for different kinds of crops. A head for beans or small grains, illustrated in Figure 5.7, cuts and gathers the stalks and pods with a cutter bar and rotating reel. A head for corn strips the cob from the stalk, leaving the majority of the plant in the field while sending the cob into the combine for further processing.

The crop is conveyed to the threshing unit, which detaches the grain from the ears or pods by a combination of impact and rubbing. Two types of threshing units are available: a cylinder/walker combination and a rotary feeder/separator. The cylinder/walker combination passes the cobs or pods between a cylinder and a concave, illustrated in Figure 5.7, which releases grain to a grain auger while straw enters the straw walker. The straw walker agitates the straw, sifting out grain and chaff not separated in the thresher. The rotary feeder/separator uses a large rotating shaft mounted with tines that both convey the crop through the combine and separate grain from cobs or pods. The straw drops out of the back of the

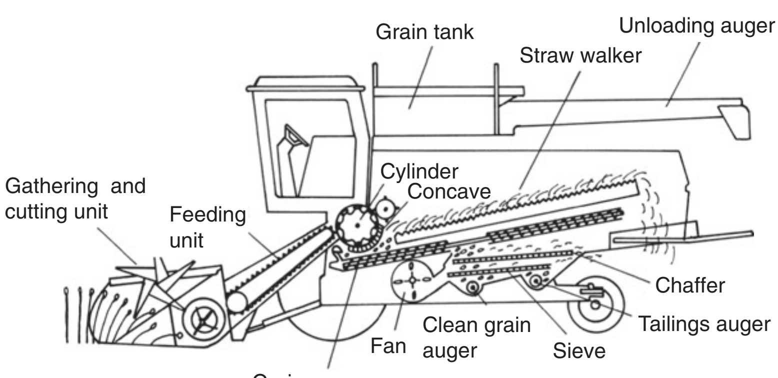


FIG. 5.7 Combine harvester. Courtesy of Deere and Company.

machine and is left in a windrow for later baling, or is baled directly by a baling attachment or press, or is scattered over the ground by a fan-like straw spreader.

Grains, as well as chaff and fragments of straw shaken out of the straw, fall into a grain auger where they pass to the main cleaning device, called the cleaning shoe. The cleaning shoe consists of one or two winnowing steps and two or three oscillating sieves. A winnowing step blows air across grain and material other than grain (MOG) as they fall from the end of the grain pan: chaff and pieces of straw are blown away while the grain falls onto a sieve (or a second grain pan, if there are two winnowing steps). The combined action of sieve oscillation and classification by airflow allows grain to penetrate the MOG layer and fall through the sieves to a grain auger which transports it to a grain tank. Material rejected by the top sieve is thrown from the back of the harvester, while material rejected by the bottom sieve(s), which may still contain significant grain, is returned to the threshing unit by a tailings return system. Correct adjustment of the air blast, by adjusting fan speed, throttling the intake of the fan, or by altering the setting of baffles, is important in determining the degree of cleaning of the grain and the magnitude of the grain losses that occur.

Forage Harvesting

Forage crops are classified according to the method by which they are ultimately prepared for storage: hay and silage. The various crops used for these different preservation methods are listed in Table 5.2. Hay is preserved by storing at low moisture levels. Both grasses and legumes are harvested, as hay with alfalfa being the most common hay crop. Silage is preserved at high moisture levels by fermenting it in the absence of oxygen, which produces organic acids that kill microorganisms that cause spoilage. Corn is most commonly employed as a silage crop. Haylage is a lower moisture version of silage, which further promotes preservation by limiting oxygen during storage. Distinctive methods of harvesting and storage are employed for these two kinds of forage crops. Hay is usually harvested in operations requiring several passes over the field, whereas silage or haylage crops are often collected in a single pass.

Table 5.2 Forage crops classified according to preservation method

Preservation Method	Crop
Hay	Alfalfa, clover, sorghum, birdsfoot trefoil, reed canary grass, smooth bromegrass, Bermuda grass, wheat grass, Canada wild rye, timothy, Russian wild rye, native grasses, cereal grains
Silage or haylage	Corn, forage sorghum, sudan grass, sorghum-sudan hybrids, oats, alfalfa, alfalfa–grass mixtures

Source: Cavalchini, A.G. (1999) Forage crops. In: *CIGR Handbook of Agricultural Engineering, Vol. III: Plant Production Engineering* (eds B.A. Stout and B. Cheze), pp. 350–374. St. Joseph, MI: American Society of Agricultural Engineers.

Since hay harvesting does not involve separation of plant parts, equipment much simpler than combined harvesting and threshing machinery can be employed. For haymaking, this involves separate steps of cutting the crop (mowing), conditioning the cut crop to improve field drying (tedding), arranging the crop into long rows in the field (windrowing), and either baling the crop or loading the loose hay into wagons. The main parameters associated with the various operations of haymaking are summarized in Table 5.3.

Mowers include rotary mowers, which cut by means of impact forces, and cutter bars, which apply shearing forces to cut the plant material. Rotary mowers have high cutting speeds (10–12 km/h) and working widths of 1.5–3 m. However, they consume 20–25 kW-h/ha, which is about 40% higher than cutter bar mowers. Cutter bar mowers employ either an oscillating knife working in combination with a fixed finger bar or a mechanism of dual oscillating elements. The former cutter bar mechanism is the more robust of the two and is better suited for cutting crops close to the ground. Cutter bar mowers have mowing speeds of 8–12 km/h and working widths of 1.5–2.5 m. Energy consumption is 18–20 kW-h/ha.

Mowers often incorporate a mechanical treatment known as conditioning, which improves the uniformity of drying time for coarse stems and fine leaves. This not only slightly reduces field-drying times but also, more importantly, prevents delicate leaves from overdrying and being lost during windrowing and baling. Conditioners can increase nutritive value of forage crops by as much as 15%. Conditioners consist of rollers for legumes or flails for grasses that slightly crush plant stems, which allows more rapid release of moisture from this coarse plant part.

As part of haymaking, after the crop is cut and partially dried in the field, it is turned and fluffed to promote additional drying. This process, known as tedding, was traditionally performed with a pitchfork. Modern machinery performs this operation by means of flexible forks on rotors mounted on a vertical axis: the forage is lifted off the ground and pitched backwards.

Windrower rakes distribute the cut crop into long rows in the field as a prelude to baling or collecting the material. Modern side delivery rakes include parallel-bar rakes and finger wheel rakes, illustrated in Figure 5.8, as well as rotary rakes. Although an apparently simple operation, the ability to efficiently rake cut forage without contaminating it with soil while operating on irregular terrain is difficult to achieve. Leaf loss is a strong function of moisture content of the crop, ranging up to 8% loss for moisture content below 30%. Large, self-propelled windrowers produce a loose, fluffy windrow, which makes tedding unnecessary. Machinery has also been developed that combines mowing, tedding, and windrowing in a single operation.

Early methods of haymaking produced piles of dry, loosely consolidated plant material known as haystacks. Mechanization allowed hay to be compressed into rectangular bales of 15–30 kg weight that were easy to handle and store, helping

Table 5.3 Unit operations of haymaking

Operation, Machine	Speed (km/h)	Average Working Width (m) or Volume (m^3)*	Capacity (ha/h,m) or (t/h)	Minimum Power (kW)	Energy Consumption (kW-h/ha) or (kW-h/t)*	Time (man-h/ha) or (man-h/t)*
Mowing:						
Walking mower (finger bar)	2–3	1.2–1.4	0.2–0.25	8	18–20	4–5
Finger bar mower	5–7	1.5–2.5	0.4–0.5	15	18–20	0.8–1.6
Double knife cutter bar	6–9	1.5–2.5	0.5–0.7	15	18–20	0.6–1.2
Rotary disc mower driven from below	9–10	1.5–3.0	0.7–0.8	25	20–25	0.5–1.0
Rotary drum mower from the top	10–12	1.5–2.5	0.8–0.9	30	20–25	0.6–0.9
Tedding: rotary tedder	10–14	2–6	1.5–6	20	10–15	0.2–0.7
Windrowing:						
Rotary rake	7–9	3–6	0.3–0.4	25–30	18–20	0.6–1.5
Parallel bar rake	6–7	2–3	0.25–0.35	15–20	15–18	1.0–2.0
Finger wheel rake	6–8	2–5	0.25–0.35	15–20	15–18	0.7–2.0
Mowing + Windrowing:						
Rotary drum mower driven from the top	10–12	1.5–2.0	0.8–0.9	30	20–25	0.6–0.9
Loading:						
Forage self-loading wagon	4–6	1.2–2.0	0.6–1.2	30	15–20	0.8–1.5
		15–30*	15–20*			
Baling: conventional baler	4–6	1.0–1.8	2–8	25–45	1.8—2*	0.13–0.5*
Round baler	5–7	1.5–2.0	2–8	40–60	2.0–2.2*	0.13–0.5*
Big baler	6–8	1.8–2.2	10–15	70–100	1.9–2.1*	0.07–0.1*
Stack-wagon	4–6	1.6–2.0	10–15	40–70	1.5–1.8*	0.007–0.1*

Source: Cavalchini, A.G. (1999) Forage crops. In: *CIGR Handbook of Agricultural Engineering, Vol. III: Plant Production Engineering* (eds B.A. Stout and B. Cheze), p. 354. St. Joseph, MI: American Society of Agricultural Engineers.

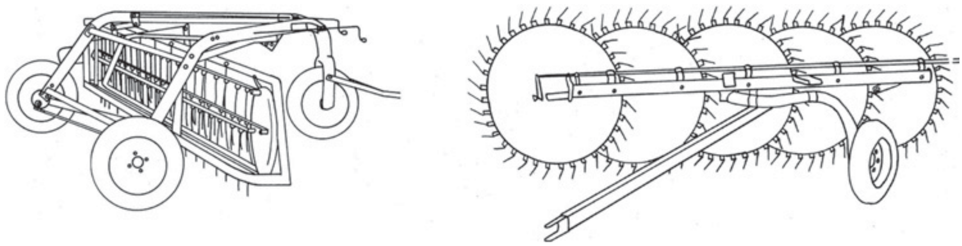


Fig. 5.8 Two types of hay rakes: (a) parallel-bar rake; (b) finger wheel rake. Courtesy of Deere and Company.

reduce the labor for forage harvesting from 40 man-hours/ha to 20 man-hours/ha. However, with continued mechanism of agriculture, this conventional bale proved to be a bottleneck to further productivity improvements in haymaking. Modern handling systems include development of big bales and round bales, weighing as much as 700 kg, and systems for collecting loose hay in self-loading wagons or stack wagons. Pelletizing or cubing of forage to high densities (approaching 450 kg/m^3) has been explored as a means of facilitating handling and storage. Although technically feasible, the approach has only limited commercial application because of high capital costs as well as energy costs in the range of 25–30 kW-h/t.

Figure 5.9 illustrates a big baler. Compression is usually achieved in two phases: in a prechamber, the forage is accumulated and partially pressed followed by final compaction in the upper compression chamber. In the upper chamber a plunger compresses the bales to densities in the range of 180–230 kg/m^3. Five to six binders are applied to hold the bale together. The bale length of 2.4 m is comparable to the length of trucks designed to haul them. Offsetting the high collection rate of 15 t/h or higher are high power requirements of the baling machine.

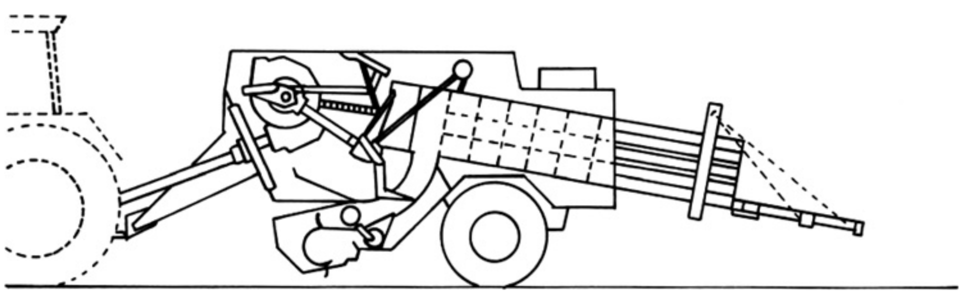


Fig. 5.9 Rectangular big baler. Adapted from *CIGR Handbook of Agriculture Engineering, Vol. III: Plant Production Engineering*, B.A. Stout and B. Cheze, eds. St. Joseph, Mich.: American Society of Agricultural Engineers, 1999.

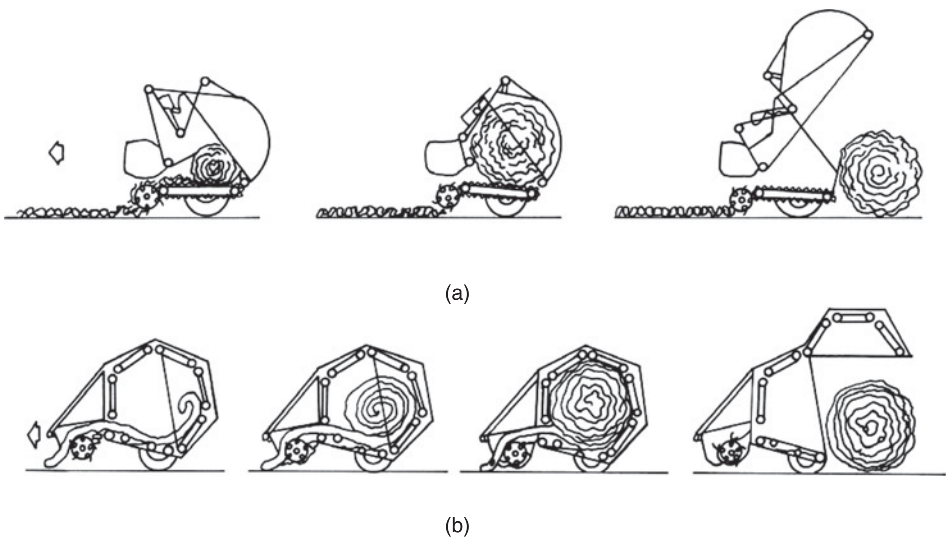


FIG. 5.10 Two kinds of round balers: (a) variable chamber, core compacted; (b) fixed chamber, loose core. Adapted from *CIGR Handbook of Agriculture Engineering, Vol. III: Plant Production Engineering*, B.A. Stout and B. Cheze, eds. St. Joseph, Mich.: American Society of Agricultural Engineers, 1999.

Figure 5.10 illustrates the two kinds of round balers: loose core and compact core. The loose core baler forms the bale in a chamber of fixed volume, which permits the bale to form around a relatively fluffy center with the periphery becoming more compact as the chamber fills. The disadvantage of reduced density is offset by greater air circulation within the core, which promotes additional drying without heat buildup after baling. The compact core baler employs a variable volume compression chamber, which provides constant compression during the accumulation of hay in the chamber.

Some parts of the world use self-loading wagons, illustrated in Figure 5.11, to harvest hay. They consist of a trailer with high sideboards and a cylinder type pickup combined with a forage chopping system. The chopping system produces lengths of hay that are 20–40 cm long for barn drying and 8–10 cm long for silage.

Stack wagons produce a fairly compact haystack of density between 100 and 150 kg/m^3 with sloping top able to shed rainfall. The wagons, pulled by a tractor, have flail type pickups consisting of horizontal rotors with flails or knives attached, which apply shearing forces on the forage. The forage is kicked up and transported pneumatically to a large, rectangular compression chamber constructed of sheet metal. The top surface is a movable canopy that allows the load to be compressed as the chamber is filled. Stack wagons are often employed to create winter feed stores left on the field. The storage density and volume, bale weights, tractor power and

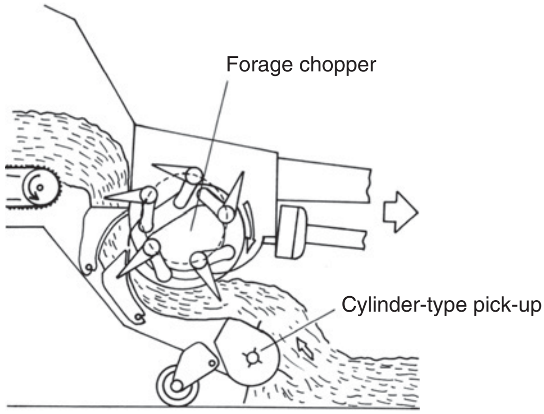


Fig. 5.11 Self-loading wagon for hay harvest. Adapted from *CIGR Handbook of Agriculture Engineering, Vol. III: Plant Production Engineering*, B.A. Stout and B. Cheze, eds. St. Joseph, Mich.: American Society of Agricultural Engineers, 1999.

energy requirements, and collection rates for these various options are summarized in Table 5.4

Forage cereals, by virtue of their high-soluble sugar content, must be ensiled for successful storage. Thus, harvesting occurs at relatively high moisture content, in the range of 32–38% depending on the kind of cereal. Forage harvesters can either collect windrowed material or cut a standing crop. Forage heads include windrow

Table 5.4 Characteristics of different hay collection methods

Collection Method	Hay Density (kg/m^3)	Bale/Stack Dimension or Wagon Volume		Weight (kg)	Energy Requirement (kW-h/t)	Collection Rate (t/h)
Self-loading wagon	<100	10–20 m^3		1000–3000	1–1.2	4–4.6
Stack wagon	100–150	Length (m)	2–5	1000–6000	1.5–1.8	10–15
		Width (m)	2–3			
		Height (m)	2.5			
Conventional bale	125–165	Length (m)	0.7–1.2	15–30	1.5–2.5	4–8
		Width (m)	0.40–0.5			
		Height (m)	0.35–0.45			
Big bale	180–230	Length (m)	1.0–2.4	200–700	2–2.5	10–20
		Width (m)	0.8–1.2			
		Height (m)	0.5–1.0			
Round bale	130–205	Length (m)	1.0–1.8	200–700	2–2.5	4–12
		Dia. (m)	1.0–1.8			

Source: Cavalchini, A.G. (1999) Forage crops. In: *CIGR Handbook of Agricultural Engineering, Vol. III: Plant Production Engineering* (eds B.A. Stout and B. Cheze), pp. 350–374. St. Joseph, MI: American Society of Agricultural Engineers.

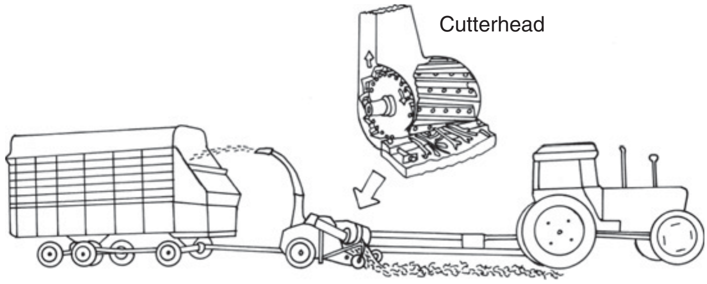


Fig. 5.12 Basic forage harvester operation. Courtesy of Deere and Company.

pickup for haylage, mower bar for winter cereals or standing grasses, and row crop for corn silage. The forage is then fed to cutterheads, illustrated in Figure 5.12, that chop the forage to suitable size, typically 6–9 mm for maize and winter cereals and 20–30 mm for grasses.

Machinery is being developed for the simultaneous harvest of corn grain and stover. Conventional combine harvesters collect the grain and leave stalks, leaves, husks, and cobs, collectively known as stover, in the field. If stover is to be harvested, a second pass over the field is required. A more economical approach to the collection of clean stover is to pick it up at the time the grain is harvested. Gathering heads have been adapted to combine harvesters that process the whole plant, sending the stover to a storage bin separate from that for grain. These systems show promise in producing stover free of dirt and containing essentially all the cobs. The amount of residues left on the field can be adjusted according to local soil conservation needs.

Cane Harvesting

Sugar cane can be harvested either as whole cane, the traditional method of harvesting, which can be done either manually or mechanically, or as chopped cane, which was developed for harvesting by power-driven equipment. Whole cane harvesting is practiced where labor is inexpensive or where a gradual transition to mechanization is desired to prevent disruptions in existing harvesting and processing infrastructure. It also produces a very clean crop, important in fiber production. Chopped cane harvesting reduces multiple steps of traditional harvesting into a single machine. Early attempts to adapt machines to local climate and geography have been abandoned in favor of field and crop management practices that are conducive to mechanical harvesting, such as leveling ground and growing lodging-resistant varieties of sugar cane.

Manual cutting of whole cane involves three operations: cutting the cane at the base; trimming off the top; and laying the canes in windrows or heaps. Loading the windrowed or heaped canes onto wagons for transport completes the harvest. Mechanization of whole cane cutting imitates one or more operations of cutting, trimming, and windrowing. Some machines simply cut the cane and require follow-up by human laborers or machines, while other approaches completely mechanize the cutting operations. Loading of either windrowed or heaped cane is performed discontinuously with front-mounted tractor loaders, self-propelled front-end loaders, swivel loaders, or power loading trailers. Windrowed cane allows the option of continuous loading by means of wide chain elevators that pick up the whole canes, chop them into 40–50-cm lengths with circular saws, and drop them into a following wagon.

Chopper harvesters completely mechanize the harvesting operation, including the loading of cane into a trailer. The cane is cut at the base, chopped into 20–40-cm lengths, and loaded directly into a trailer. The cane can be chopped immediately after cutting, which is known as "bottom chopping" (i.e., near the ground), or after it is conveyed through the machine, which is known as "top chopping" (i.e., elevated from the ground). The advantage of bottom chopping is reduced power requirement by the machine. The advantage of top chopping is that cutting blades are protected from dulling by soil and rocks.

The method of transporting cane to sugar mills depends on the distance involved. Field tractors and trailers are frequently used for distances of less than 10 km. High-capacity road trailers or tractor trailers are used for longer distances. Occasionally, private rail systems are employed for large production systems. In any case, cut cane must be delivered to the mill and crushed within 25 hours if the field was burned before harvest, or within 48 hours if cut green to prevent sugar loss.

5.3 Woody Crops

The term short rotation woody crop (SRWC) is used to describe woody biomass that is fast growing and suitable for use in dedicated feedstock supply systems. Desirable SRWC candidates display rapid juvenile growth, wide site adaptability, and pest and disease resistance. Promising tree species include poplar (*Populus* spp.), willow (*Salix* spp.), silver maple (*Acer saccharinum*), sweet gum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*), black locust (*Robinia pseudoacacia*), and *Eucalyptus* spp. Trees of potential regional importance in the United States include alders (*Alnus*), mesquite (*Prosopis*), and the Chinese Tallow (*Sapium sebiferum*).

Hybrid poplar and eucalyptus are most promising for the United States because of high growth rates ranging between 20 and 43 Mg/ha/year. In the United States, hybrid poplar has a wider range than eucalyptus, which is limited to southern Florida, California, and Hawaii. Hybrid poplar is also attractive for the ease of propagating it from either stem cuttings or tissue culture.

5.3.1 Site Preparation

Short rotation woody crops need to be established under conditions similar to those for herbaceous crops. Deep, well-drained fertile soils with adequate rainfall provide the best yields. Light textured soils such as sandy loams or silty loams are preferred, but heavier textured soils can be employed with sufficient drainage. Thus, suitable acreage ranges from good cropland to land that is marginal for conventional crop production because of poor drainage or erosion potential.

Although hybrid poplar may have the best overall potential for dedicated feedstock supply systems, other species are better adapted to certain regions or marginal lands. Sycamore and sweet gum are more suitable for Southeastern United States where respiration rates are higher and drought more common. Silver maple is well adapted to bottomlands susceptible to flooding, while black locust, which can extract nitrogen from the atmosphere (nitrogen fixation), can be grown on nutrient-poor soils. SRWCs are unsuitable for cutover upland forest sites because of generally thin soils, low fertility, and susceptibility to erosion.

Site preparation should begin 1 year before planting. Abandoned cropland or pasture typically requires brush removal, mowing, plowing, and application of broad-spectrum herbicide to eliminate competing plants. Conversion of row-crop fields to SRWC may only require a single spring plowing and row-marking operation. Conventional farm tractors and implements, such as moldboard plows, discs, and harrows, can be used for site preparation.

5.3.2 Seeding and Planting

Seeding is not directly employed to establish trees in dedicated feedstock supply systems. Instead, bareroot seedlings, containerized stocks, or cuttings are planted in the prepared site. Large-seeded species can be sown in beds where they sprout and grow into seedlings that are transplanted as bareroot seedlings. Containerized stocks are trees grown in plastic or fiber pots, which generally produces trees with higher survival rates upon field planting than do the alternative propagation methods, but at a cost that is 25–250% higher than the alternatives. Cuttings are plants reproduced by clonal propagation, a process by which the tissue taken from the root, stems, or leaf of a plant is grown into a whole plant that is genetically identical to the original plant. Clonal propagation is favored for dedicated feedstock supply systems, because trees with the most desirable properties, such as disease resistance or rapid growth under specific local site conditions, can be selected and rapidly multiplied.

In some instances, clonal propagation requires culturing the vegetative tissue in special “cloning solutions” until roots are established at which point the cutting can be planted to the field or a container. However, cuttings from many hardwood species can be planted directly into the ground. Most planting material is a 25-cm-long hardwood cutting with diameters of 1–2 cm. Species that sprout and grow readily include many *Eucalyptus* spp., *Populus* spp., and *Chlorophora excelsa*.

Spacing of plantings is critical as it affects establishment costs, optimal rotation ages, and tree size at harvest. Optimal spacing is a function of the tree species, soil quality, climate, and desired size at harvest. Narrow row spacing has the advantage of allowing tree crowns to shade out competing weeds within 3 or 4 years and reducing branching. Tree spacing ranges from $1 \times 1\ m^2$ for willow plantations that are harvested every 2–3 years (10 000 trees per hectare) to $4 \times 4\ m^2$ for large saw logs (625 trees per hectare). Planting densities of 1500 trees/ha might be considered typical. Both hand planting, at rates of 4 ha/day/person, and machine planting, at rates of 16 ha/day for a three-person crew, have been employed. Machine planting can be problematic in rocky soils, wet soils, or poorly prepared soils.

5.3.3 Fertilizer Application

Fertilization is required to maintain rapid growth rates as well as maintain the fertility of the soil. For trees planted to fertile bottomlands, application of fertilizer may not be required until the second rotation of SRWC. Most sites will require nitrogen application by the third year. Granular nitrogen fertilizer can be applied by either ground or aerial equipment. Ground application of granular nitrogen is done with cyclone-type applicators.

5.3.4 Pest Control

Good survival and growth of SRWC can be achieved compared to either HEC or conventional crops if the site is thoroughly prepared and planted with fast-growing clones. Herbicide applications before and after planting are usually employed to reduce labor of hand and mechanical weed control. Rotary hoes can be used to till newly established plantations on light (sandy) soils to control emerging weeds until the trees are 30 cm tall.

A large number of animal and microbial pests must also be controlled. These include deer, elk, beavers, voles, and gophers in the first two years of establishment and insect and fungal species in even well-established stands. The best strategy is to select species and clones that are best adapted to pests indigenous to the region. For example, hybrid poplar is a poor choice for eastern United States because of insect and fungal pests. In some circumstances, application of insecticides or fungicides may be required to control these pests.

5.3.5 Harvesting

Rapid juvenile growth and high carbon sequestration rates can be sustained only if the stands are regularly harvested. Typically, rotations are no longer than 8–10 years as growth rates peak after 4–6 years and quickly slow as a result of competition among the trees.

Harvest should occur during the dormant season, which allows significant translocation of nutrients to the roots or returned to the soil by leaf fall. This assures rapid growth of coppice the following spring. There is little data on long-term productivity of SRWC grown in coppice systems. Some economic analyses project that stands will be harvested only three times, representing a total time period of 15–30 years before they are replaced with improved tree varieties.

Harvesting equipment for traditional logging operations was developed for broken terrain typical of upland forests as opposed to the relatively flat agricultural lands to be planted to SWRCs. Much of it is adapted for coniferous (softwood) trees that are larger and less uniform than the deciduous (hardwood) trees of interest for dedicated feedstock supply systems. Thus, an evolution of harvesting equipment can be expected for woody crops as the industry develops.

Harvesting in the near term will employ several pieces of machinery familiar to the conventional logging industry. A feller/buncher, illustrated in Figure 5.13, performs the initial operation of cutting the trees (felling) and stacking them (bunching). The self-propelled machine, which is either rubber-tired or tracked, has an articulated, extensible arm at the end of which is a felling head. The felling head consists of a grappling device and either a disc or a chain saw. The human operator uses the grappling device to grasp the trunk of a single tree or possibly the trunks of up to six small trees. The saw severs the tree trunk from the stump, and the operator maneuvers the articulated arm to rotate the trunk to a horizontal position and lay it into a pile of felled trees.

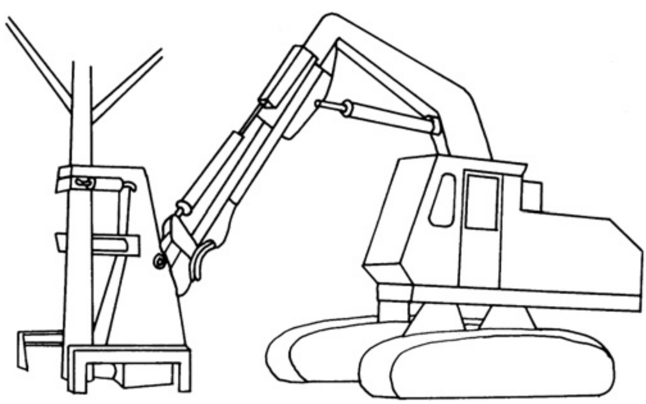


Fig. 5.13 Feller/buncher for cutting and piling woody crops.

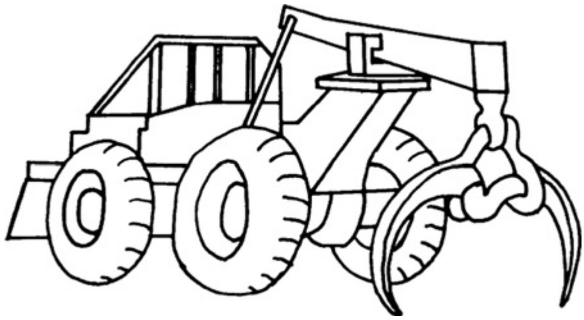


Fig. 5.14 Grapple skidder for moving piles of felled trees to a "landing" for further field processing.

A grapple-equipped skidder, illustrated in Figure 5.14, transfers the pile of felled trees to a centralized "landing" for further processing. The grapple skidder is a rubber-tired, four-wheel drive vehicle with a dozer blade on front and a maneuverable grappling device on the back. The skidder is backed into position next to a pile of trunks and the grapple used to pick the pile off the ground before transporting it to the landing.

At the landing, limbs and bark are removed mechanically usually by a flail, which is a rotating drum fitted with lengths of steel chain that batter the tree trunks, breaking off limbs and shattering bark. The mixture of bark and limb wood is usually suitable only as fuel wood. The delimbed and debarked tree trunks are then feed to a tub grinder, also located at the landing, which produces chipped pulpwood suitable as feedstock in processing to chemicals or fibers. The combined operations of delimbing, debarking, and chipping are illustrated in Figure 5.15.

Flail delimbing and debarking is the bottleneck in producing clean feedstock from woody crops. High production rates yield unacceptably high levels of bark

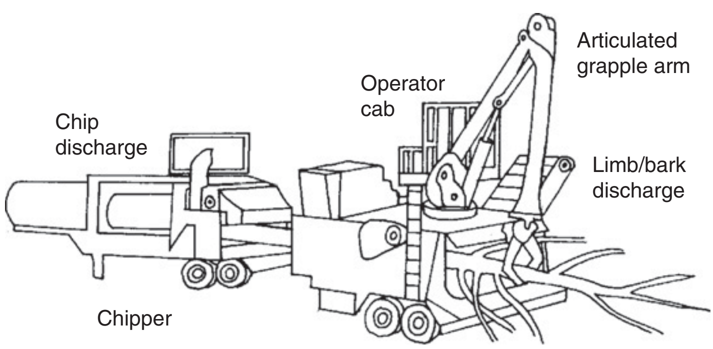


Fig. 5.15 Flail delimber/debarker/chipper operation.

mixed with the pulpwood, which must be less than 1% to be suitable. Furthermore, the process entails relatively high operating costs, including energy consumption (40–70 MJ per dry Mg of residues) and chain replacement.

Equipment optimized for harvest of SWRCs are still being developed. Some of these resemble the mechanical harvesters that are used to cut and collect bundles of sugar cane stalks. Others are essentially heavy-duty forage harvesters like those used to chop corn stalks into silage except with larger cutting heads. This development will probably proceed slowly until widespread commercial markets develop for the pulpwood.

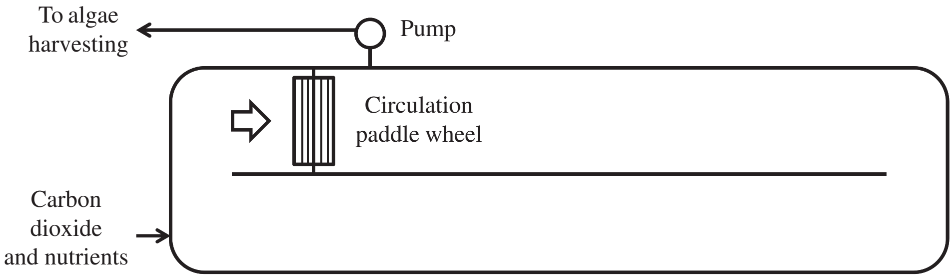
5.4 Production of Oleaginous Species

As described in Chapter 4, oleaginous species are very diverse, ranging from oil seed crops like soybeans to nonvascular (typically aquatic) species like microalgae. The methods for cultivating and harvesting oleaginous crops are just as diverse. For more exotic oleaginous crops, such as salicornia, these methods have not been well established.

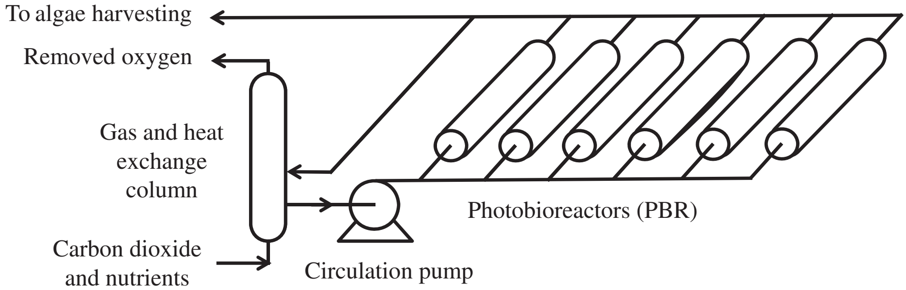
Rather than presenting a comprehensive review of cultivation and harvest of oleaginous crops, this section focuses on microalgae, which have the greatest potential for large-scale production of lipids for processing into fuels and chemicals. Readers interested in oil seed crops should refer to Section 5.2 of this chapter for a description of cultivating and harvesting grain crops, which utilize similar methods and equipment.

5.4.1 Microalgae Cultivation

Most schemes for large-scale autotrophic cultivation of microalgae, whether marine or fresh-water species, are envisioned to be land based using specially constructed open raceway ponds or closed tubular photobioreactors (PBRs). Open raceway ponds, illustrated in Figure 5.16(a), are shallow, oval-shaped containments split in the middle to allow water to be circulated around them, usually by the action of a paddle wheel. Raceway ponds may encompass 300–4000 m^2 with an average depth of 20–30 cm. Carbon dioxide and nutrients are injected into the pond to encourage high microalgae productivity, which is typically in the range 5–35 $g/m^2/day$. Evaporation from the open ponds can help moderate heat gain associated with absorption of sunlight, but this also exacerbates water loss. Phase change liquids are sometimes floated on the surface of the ponds to reduce both water loss and heat gain. Raceway ponds have the advantage of simple design and construction. Because they are open to the environment and prone to contamination, neither conventionally bred nor genetically modified organisms can be cultivated in raceway ponds, which would be outcompeted by wild strains of algae.



(a)



(b)

Fig. 5.16 Algae cultivation systems: (a) open raceway pond (top view); (b) closed PBRs.

Tubular PBRs, illustrated in Figure 5.16(b), are usually installed horizontally, although some pilot-scale reactors are installed at an angle to the horizon to improve solar insolation. The diameter of the tubes is about 10 cm. A pump continuously moves water and suspended algae through the reactors, heat exchangers, and gas exchangers. If properly designed, algae productivity can be 14–48 g/m^2/day. Compared to raceway ponds, closed tubular PBRs have the advantages of lower contamination risk, less water loss, almost no carbon dioxide loss, less complicated process control, reduced susceptibility to weather, and land requirements that are only 30% of that of open raceway ponds. On the other hand, they have increased risks of overheating and excessive dissolved oxygen levels. The greatest disadvantage is their high construction costs, which can be 10 times higher than for open raceway ponds.

Another possibility for growing microalgae is open ocean cultivation in regions of the world known as high nutrient, low chlorophyll (HNLC) areas. These regions have sufficient nutrients to support the growth of algae or other aquatic species except for the absence of certain micronutrients, especially iron. Some researchers have proposed fertilizing HNLC regions with iron, which would promote rapid growth of autotrophic microorganisms. Although originally proposed as a way to promote ocean photosynthesis for the purpose of sequestering carbon from the atmosphere, the biomass could be harvested for bioenergy production instead of sequestering it in the ocean. Limited experimental trials have proven that ocean fertilization can enhance photosynthesis, but the environmental impacts have not been sufficiently evaluated and harvesting microalgae in the open ocean would be challenging.

5.4.2 Microalgae Harvesting and Water Removal

Harvesting microalgae involves unique challenges compared to harvesting vascular plants. Optimal growth requires low algae concentrations in water (about 50 mg/L or, on a mass basis, 500 parts per million) and continuous harvesting. On the other hand, processing of biomass requires solids loading of at least 20–30 wt% (wet processing) or even moisture contents as low as 10–15% (dry processing). Methods for recovering microalgae and removing water ahead of processing are still under development, but resemble in many respects those used in wastewater treatment. Solids recovery is often conducted in stages, incrementally decreasing the moisture content of the microalgae. These stages, illustrated in Figure 5.17, include screening, thickening, dewatering, and drying.

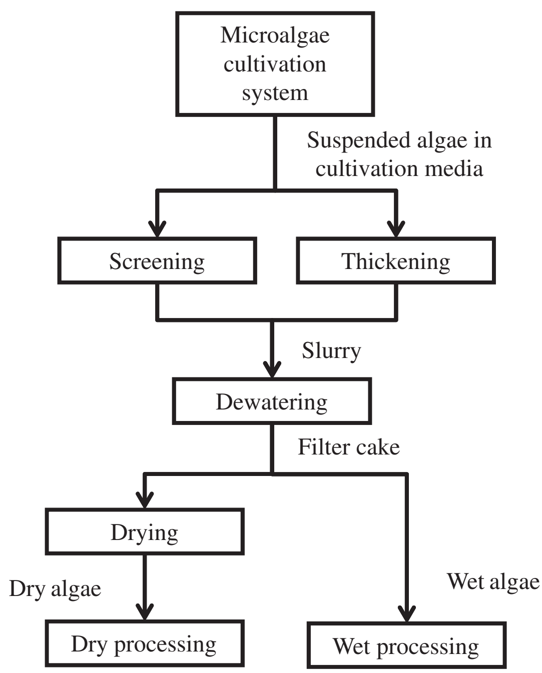


Fig. 5.17 Flow diagram for algae harvesting and solids recovery.

Screening, when employed, is the first operation in solids recovery with the goal of increasing solids concentration two orders of magnitude above the typical 0.05% solids concentration of the microalgae growing in water. Although able to process large volumes of water at relatively low cost, success is dependent upon screen apertures being smaller than the size of the microalgae. For some microalgae species, with cellular diameters as small as 5–10 μm, this can be challenging. Screening can remove up to 95% of the microalgae suspended in water and yield algal slurry containing 6–10% solids.

Thickening is an alternative to screening. Thickening can be achieved through several techniques including gravity sedimentation, flocculation, and flotation. Gravity sedimentation simply transfers the cultivation media to a quiescent settling tank or basin and allows suspended algal cells to settle out by the action of gravity. Flocculation is the process of encouraging single cells of algae to agglomerate into large cell masses (flocs), which can occur naturally or by the addition of chemicals. Clearly, flocculation would increase the ease and efficiency of screening or the speed of gravity sedimentation. Flotation is used for very light suspended particles, which do not readily settle by gravity. Air bubbles are admitted to the bottom of the flotation tank, which attach to the algae and make them light enough to float to the surface where they accumulate, allowing them to be readily skimmed off. Flocculation can increase the efficiency of flotation.

Dewatering has the goal of sufficiently reducing the water content of slurries produced by thickening to be handled as a solid, sometime known as filter cake. Dewatering, possibly occurring in stages, typically increases solids content from 2–10% to 12–35%. Major dewatering operations include several kinds of filtration and centrifugation. Filtration, in contrast to the removal of solids from water by screening, is the removal of water from solids. Filtration can be either surface or deep granular bed phenomena. In either case, some kind of backwash or granular media cleaning must occur periodically to sustain the process. Different kinds of filtration include pressure filtration, vacuum filtration, granular bed filtration, magnetic filtration, and cross-flow ultrafiltration. Centrifugation involves imparting high centrifugal forces on the algal slurry, causing separation between the denser solids and the lighter water. Several variations of centrifugation have been developed, including solid-bowl decanter centrifugation, nozzle-type centrifugation, and solid-ejecting disc centrifugation. Dewatering, although relatively low energy compared to drying, consumes significant power to develop the pressures or velocities required for their effective operation. Dewatering consumes as much as 40% of the total power required to grow, harvest, and process algal biomass.

Drying is the application of heat to filter cake to reduce moisture content to the range of 10–15%. The decision to dry the biomass depends upon whether dry or wet processing is desired. These alternative processing approaches are discussed in Chapter 9. Since the starting moisture of filter cake is usually on the order of 80%, significant heat energy is required to dry it. When employed, drying constitutes

70–75% of the processing cost. The kind of drying method employed depends on the scale of the operation and the ultimate use of the dried product. The major classes of drying equipment include direct-fired rotary dryers, steam-heated rotary dryers, spray dryers, cross-flow dryers, and vacuum-shelf dryers.

5.5 Storage of Herbaceous and Woody Biomass

Agricultural production is seasonal, with crops being harvested only once or just a few times per year, while processing to energy, fuels, chemicals, or materials is a year-round activity since manufacturing facilities are too expensive to remain idle most of the year. Most biomass undergoes substantial degradation in the course of a few months or even days if exposed to the elements after harvest. Accordingly, proper storage to preserve plant materials for periods of a year or even longer is critical to the successful development of a biobased products industry. Traditional methods of long-term storage involve drying, cooling, or ensiling a crop or immediately processing the crop to obtain a more stable intermediate product. Each has its advantages and disadvantages, the choice depending on the nature of the crop and the kind of processing it will ultimately undergo.

5.5.1 Drying

Drying removes moisture from a crop to the levels that impede growth of microorganisms. Freshly cut biomass may have a moisture content of 60% or higher for woody biomass and 70–85% for herbaceous biomass. This moisture exists in two forms: free water within the pores of the plant material and bound water absorbed in the interior structure of the material. Successful preservation of plant material may require drying to as little as 10% moisture. Drying is a very energy-intensive process, theoretically requiring 2442 kJ of energy for every kilogram of moisture removed at 25°C. Actual drying, which is often performed at temperatures slightly higher than 100°C, requires about 50% more thermal energy than this theoretical level to account for sensible heat of both the biomass and the air used for drying. To dry a ton of biomass containing 50% moisture to 10% moisture would require about 1.5 GJ of energy, representing about 18% of the energy content of the fresh biomass. Thus, field drying is employed whenever possible.

A crop left standing in a field beyond maturity will naturally dry, as is commonly done for such crops as corn, soybeans, and wheat. Green crops can also be cut and left lying in the fields to dry, as is commonly practiced in haymaking. The level of drying depends upon the climate, the kind of crop, and the structure of the plant part. For example, leaves dry more readily than stems and plant parts protected by pods or husks will dry more slowly than exposed plant parts. In many regions of the world, grasses can be field dried to moisture levels consistent with long-term storage. Many grains, though, protected as they are by pods and husks, require additional drying in grain silos after they have been harvested, depending on local climatic conditions.

Barn drying of hay is employed in climates where field drying is not practical. After the forage is cut, it is allowed to field dry down to a moisture content of 40–45%. The material is then collected with a self-loading wagon as previously described and stored in a drying barn where either ambient air or air that has been heated 10–20°C above ambient is circulated through the hay to reduce the moisture to around 15%. Barn drying is often employed in small to medium dairy farms.

Baling, as previously described, is appropriate for hay and crop residues, such as corn stover. Conventional balers do not yield sufficient compaction for economic storage, especially for stalks. Large round or square bales are more appropriate for long-term storage. Large round bales can be stored outside for several months, but there can be some losses due to water damage and weathering. Bales can also be wrapped in polyethylene sheets, canvas, or nylon tarpaulins for field storage, which helps shed water. Ideally, bales are stacked in sheds to protect them from the weather. Handling of baled crops is very labor intensive, which makes this mode of storage unattractive in places where development has increased the cost of labor.

5.5.2 Cool Storage

Storing biomass in a cool, dry environment is also an effective method for discouraging microbial degradation. Farmers traditionally used root cellars, consisting of excavations into hillsides, as a cool place to store tubers for periods longer than would otherwise be possible for these relatively high-moisture crops. Today refrigerated rooms are used to store high-value crops, such as seed corn, but use of cool storage is not practical for commodity crops.

5.5.3 Ensiling

Ensiling was developed for humid climates where field drying is impractical, but it is finding increasing application in drier climates. Ensiling is attractive for automating the handling and storage of cereals, grasses and legumes, bagasse, and even cornstover, the latter of which is typically much drier than traditionally ensiled crops. Grasses and other graminaceous species are easier to ensile than legumes, the protein content of which promotes butyric fermentations associated with rotting of the forage.

The crop is ideally harvested at a moisture content of 40–50% and stored under anaerobic conditions to promote partial fermentation of sugars to organic acids, which suspends further microbial degradation of the crop. Chemical additives, usually organic acids, water-soluble salts, or pulverized limestone, are sometimes added for pH control.

Storage systems include horizontal silos and vertical silos. Horizontal silos include bunkers, consisting of an above ground structure of concrete floors and walls; trenches dug into the ground, with either bare earth or concrete floors and walls; large polyethylene bags; and unprotected stacks for temporary storage. Vertical silos include conventional silos, constructed from metal, concrete, or tile, and oxygen-limiting units usually constructed of metal with an inner lining of fused glass. The technology is relatively easy to implement and requires no direct energy input.

Losses during ensiled storage are inevitable. If properly preserved, biomass losses can be kept to only 5–10%, depending upon the sugar content of the ensiled material (e.g., bagasse, the fibrous stalks remaining after expressing juice from sugar cane, has a relatively high residual sugar content). Improper ensiling can result in losses as high as 30%.

5.6 Transgenic Crops

For thousands of years, mankind has employed plant breeding to improve yields of sugars, starch, oil, and protein in crops, increase resistance to pests, and adapt plants to local climatic conditions. In conventional plant breeding, genes already existing within a species are brought together in new combinations by sexual crossing in an effort to express desirable characteristics. Statistical laws control the possible outcomes, but careful selection of offspring with desired traits makes the process deliberate. Recent advances in biotechnology broaden the scope of plant breeding by allowing selection of desirable traits across species, thus the name *transgenic crops*. Because genetic material is directly manipulated, the process is also less probabilistic, the outcomes known a priori.

5.6.1 Genetic Manipulation

The process of creating a transgenic plant, illustrated in Figure 5.18, begins by identifying an organism, whether bacteria, plant, or animal, that contains the desired trait to be expressed in the new plant. The expression of this trait is mediated by various proteins that serve as catalysts for biochemical reactions or as

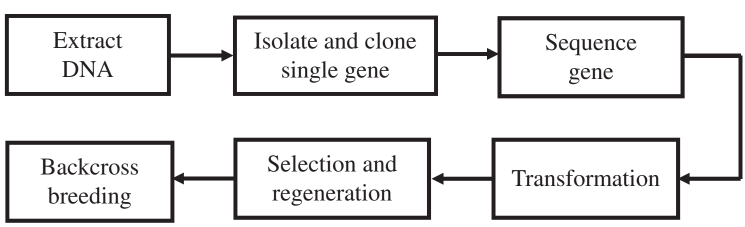


FIG. 5.18 Steps in producing a transgenic plant.

building blocks for cellular components. The genetic roadmap for manufacturing these proteins is the organism's deoxyribonucleic acid (DNA), usually contained within the cell nucleus. Because all organisms employ similar mechanisms for transcribing and translating the information contained in DNA into proteins, the DNA from one organism, in principle, can be inserted and used in another organism.

A gene is a segment of DNA that controls assembly of a particular protein. Thus, after *extracting* DNA from the organism that expresses the desired trait, the next step is to isolate the gene that produces the protein associated with the trait. Although tremendous strides have been made in "mapping" DNA for various organisms, the process of identifying and locating genes for agriculturally important traits will limit the rate of introduction of transgenic crops for several years to come. Usually, it is not enough to know which stretch of DNA produces a particular protein since other genes may also interact with the biochemical pathway to be manipulated. However, once the gene has been identified, it can be *isolated* by the use of restriction enzymes, which recognize and cut phosphate bonds at specific locations along the backbone of the DNA molecule, and further manipulated with ligases, enzymes that join fragments of DNA. The isolated gene is inserted into bacteria where it is replicated, or *cloned*, in sufficient quantities for subsequent genetic manipulations.

The isolated and cloned gene requires further genetic manipulation, called *sequencing*, before it can be successfully expressed as a transgene in a host plant. As shown in Figure 5.19, this entails the addition of a selectable marker gene, a promoter sequence, and a termination sequence. The selectable marker gene is added as a means of identifying which plant cells have successfully integrated the transgene, since the insertion process has a relatively low probability of success. Selectable marker genes encode proteins that confer resistance to agents that are normally toxic to the plant being transformed. For example, the marker gene might protect against an antibiotic or herbicide. Thus, plants that successfully incorporated the transgene are identified by treatment with the toxic agent and selecting the surviving plants. The promoter sequence is the on/off switch that controls when and where the plant gene will be expressed. A "constitutive" promoter is commonly employed, which causes the gene to be expressed throughout the life cycle of the plant in most tissues. Other promoters respond to specific environmental cues, such as light. The termination sequence simply indicates to the cellular machinery that the end of the transgene has been reached.

Transformation is the process of inserting the transgene into the desired host plant. A wide variety of techniques have been developed to achieve

Marker gene	Promoter sequence	Transgene	Termination sequence

Fig. 5.19 Components of a constructed transgene.

transformation including plant viruses, chemically mediated DNA uptake, *Agrobacterium* cocultivation, electroporation, microinjection, microprojectile bombardment, and electric discharge particle acceleration.

Certain kinds of plant viruses can introduce DNA into normal, healthy plants. Transformation may be as simple as rubbing the leaves of the target plant with viruses in which the transgene has been inserted: the virus systematically infects the cells of the plant, transferring the gene into the plant's genetic material. The most commonly employed viral vector is the cauliflower mosaic virus. Viral transformation is limited to plants that it can naturally infect. They have little prospect for producing transgenic cereal crops.

Polyethylene glycol and polyvinyl alcohol, in combination with calcium ions and high pH, can produce chemically mediated uptake of DNA. The integrated gene was shown to be inheritable in subsequent generations of plants transformed in this manner. Transformation frequency is inferior to other techniques, in particular *Agrobacterium* cocultivation, but may have application to graminaceous monocotyledons (species related to grasses), which are more difficult to transform by *Agrobacterium* cocultivation, as subsequently described.

Agrobacterium cocultivation involves the coincubation of plant cells with *Agrobacterium tumefaciens*, a soil bacterium that naturally infects many dicotyledonous (broadleaf plants like soybeans and tomatoes) and gymnospermous (coniferous) plants. The DNA for this organism is contained in the bacterial chromosome as well as in a structure known as the Ti (tumor-inducing) plasmid. The Ti plasmid includes a section of DNA known as T-DNA, which is transferred to the plant cell during the infection process, and another section of DNA, known as vir (virulence) genes, which directs the infection process. To harness *A. tumefaciens* as a transgene vector, the tumor-inducing section of T-DNA is removed, while the T-DNA border regions and the vir genes are retained. The transgene is inserted between the T-DNA border regions, which is transferred into plant cells during coincubation and becomes integrated into the plant's chromosomes. The process has been widely employed because of the large number of cells that can be treated at a time and the uniform exposure that is achieved. However, many important monocotyledons, such as rice and corn, are not susceptible to transformation by this technique.

Electroporation achieves transformation by applying a high electrical potential to a mixture containing plant cells and the transgene. The process is hypothesized to induce cell membranes to a state of high permeability, allowing transgenes to diffuse into the cells, although the exact mechanism is not fully understood. Electroporation has found application to monocotyledons and other plants that are recalcitrant to other transformation processes. The advantages of this approach include inexpensive instrumentation, reproducibility, and avoidance of toxic chemicals.

Microinjection uses microcapillaries and other microscopic devices to deliver DNA into individual plant cells. The potential for microinjection was first demonstrated in rapeseed, but the technique has not advanced as much as other transformation processes. As might be expected, the process requires considerable skill and specialized instrumentation, and only one cell receives DNA per injection.

Microprojectile bombardment accelerates micron-sized particles of tungsten or gold that have been coated with DNA to velocities sufficient for nonlethal cell penetration. This "biolistics" approach requires careful refinement to avoid excessive morality of plant cells so treated. This transformation process has been extensively studied, especially for monocotyledonous species such as rice and corn. A closely related process, electric discharge particle acceleration, applies a high-voltage electric discharge to a tiny water droplet, which rapidly vaporizes and serves as propellant to DNA-coated spheres of gold. Uneven particle distribution and cell death by bombardment contribute to low transformation efficiency for these two processes.

From the above descriptions of transformation processes, it is evident that a relatively small fraction of attempts to insert a transgene into plant cells are successful. Accordingly, gene insertion must be followed by *selection and regeneration*, in which plant cells that have successfully incorporated the transgene are separated from the rest of the plant cells and grown into whole plants. The inclusion of a selectable marker gene in the constructed transgene makes this separation possible. The mixture of transgenic plant cells and normal plant cells from the transformation process is transferred to a growth medium containing the toxic agent for which the selectable marker gene affords immunity. Thus, only the plant cells that have successfully incorporated the transgene will survive, all others perish from the toxic agent.

Those plant cells surviving the selection process are grown under controlled environmental conditions in a series of growth media containing nutrients and hormones into whole plants. These whole plants generally do not possess the qualities of modern cultivars demanded by producers and consumers. Therefore, the transgenic plant will be crossed with an improved variety. This initial cross to the improved variety must be followed by several cycles of repeated crosses to the improved parent, a process known as *backcross breeding*. The goal is to recover as much of the improved parent's genome as possible, with the addition of the transgene from the transformed parent.

The final step in the process is multilocation and multiyear evaluation trials in greenhouse and field environments to test the effects of the transgene and overall performance. This phase also includes evaluation of environmental effects and food safety.

5.6.2 Biobased Products from Transgenic Crops

Genetic transformation of crops offers many opportunities for plant improvement, including resistance to herbicides, protection against insects and other pests, hardiness against frost, and the manufacture of valuable products in plants. This latter prospect has led to discussions about "plant factories" and "plant molecular farming." Biobased products that might be manufactured directly in plants to yield commercially recoverable quantities include antibodies, oligopeptides and proteins, sugar oligomers and polymers, phenolics and alkaloids, essential oils, monomers for biodegradable polymers, and enzymes for industry and therapeutic purposes.

An example of a particularly intriguing prospect is the growth of a class of industrial polymers called polyhydroxyalkanoates (PHA) in plants. This concept was based on the observation that the bacterium *Alcaligenes eutrophus* can directly synthesize poly-3-hydroxybutyrate (PHB), which accumulates as polymeric inclusions in cell bodies, from glucose. However, the relatively high cost of glucose and other suitable carbon sources makes the economics of PHA from bacteria unattractive compared to the polymers derived from fossil resources.

Since plants use carbon dioxide and sunlight for their carbon and energy sources, genetically modifying a plant to produce PHA would appear to be a more economical alternative to manufacture in bacteria. To this end, researchers engineered the enzymes controlling PHB synthesis into *Agrobacterium* plasmid, which was used to genetically transform *Arabidopsis thaliana*, a small flowering plant that is a member of the mustard (*Brassicaceae*) family, to produce polymers in plant tissues. Up to 14% PHB in dry weight of leaves has been achieved. The production of PHAs in plants has yet to be realized, as technical questions remain concerning the separation of polymers from plant tissue and the overall energy requirements of processing facilities.

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