1 A Brief History of Weeds and Their Impact

"... the sun never sets on the empire of the dandelion"

Alfred W. Crosby, *Ecological Imperialism*

Weed Classification

Weeds were, and are, the largest single limitation on crop yield. Before the onset of chemical control for weeds, most of the work on the farm from June through August was hoeing; a weed control method still practiced around the world. Without mechanization, the size of a farmer's holding and yield was determined by how well (and how fast) a family could weed its land. As suggested by Zimdahl (1993), more human labor may be expended on weeding than on any other human enterprise (Figure 1.1).

Weeds affect nearly every aspect of our lives, from the appearance of our lawns to the quality of the food we eat, even the state of our health. Weed science, a subset of botany, is a multidisciplinary science with the goal of a systematic understanding of both weed biology, and more importantly, weed control. Weed scientists represent a broad spectrum of scientific disciplines including plant physiologists, botanists, agronomists, chemists, molecular biologists, biochemists, and ecologists.

But what makes a plant a weed? If we called something a weed in the northeastern United States, would it still be considered a weed in Australia? Are there common characteristics among different weed species? In what habitats are weeds found? How do weeds spread? What makes a weed harmful? How do we measure harm? How do we manage weeds currently? How will we manage them in the future? In this first chapter we will explore these basic concepts of weed biology.

A weed is a weed is a weed? One of the greatest difficulties in introducing the subject of weed biology is a clear understanding of what is meant by "weed." The term "weed" does not exist in nature; rather, plant species assume the mantle of "weed" when classified as such by human society.

Given the diversity of societies, many weed science books will list a number of cultural and scientifically derived definitions. While varied in scope, these characterizations fall into two broad categories: "an unwanted or undesired plant species" and "early vegetation following a soil disturbance." The first classification is used by many laypersons as well as agronomists and weed scientists, the latter is a definition widely accepted by ecologists and

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Figure 1.1 The author's (LHZ) future in-laws working on a farm near Samantha, Alabama, during the early 1900s. Farm work, particularly hoeing weeds, was the main activity during the summer months, and the principal reason school children were given summers off. (Photo courtesy of Mollie Guy of Tuscaloosa, Alabama.)

environmentalists. There is also a third definition—that a weed is a plant whose virtues have yet to be discovered—suggesting that if a use were found for a weed species, it would cease to be a weed. Yet, many of the most pernicious weeds were introduced specifically because of their virtues (e.g., forage crops such as Johnson grass[1] and kudzu, as well as aesthetic species such as purple loosestrife).

Because the characterization of a weed is determined by human activity, the definition of a weed is fluid; it can vary by time and space, and certainly by culture. For example, jimsonweed, in addition to being a common weed of roadsides, is also considered an important medicinal plant for native peoples of the southwestern United States. However, certain plants are universally reviled because it is acknowledged among disparate regions and cultures that those plants can cause widespread economic or environmental damage. One such plant is Canada thistle, considered among the worst weeds in North America (Skinner et al., 2000) for its ability to invade, colonize, and out-compete native and agricultural vegetation. In

[1] Common names of weeds will be used throughout the book, scientific names, Bayer and WSSA codes are referred to in the appendix

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these cases, the definition of a weed is less in doubt because the impact of these plants is universally recognized.

Ultimately, the definition of "weed" is anthrocentric and therefore flexible; however, "weeds" in many societies share certain biological characteristics.

The following is a synthesis of some of these characteristics, most notably those presented in Zimdahl (1993) and Radosevich et al. (1997). No single weed possesses all of these attributes, but these characteristics encompass biological traits associated with "weediness."

1. Long-term seed survival in the soil, including resistance to microbial degradation. In addition, weed seeds can germinate over a wide range of environmental conditions. Soil disturbance may be needed for germination.
2. Rapid growth following germination.
3. Mechanical (e.g., spines) and chemical (e.g., poison) barriers to herbivory during vegetative growth.
4. Grow over a wide range of environmental conditions, including extremes of temperature, water, and nutrient availability; high environmental plasticity.
5. Flower early during vegetative growth. Time from flowering to seed production can be rapid (e.g., 2 weeks from flowering to mature seed for Canada thistle).
6. While some weeds are self-compatible, most cross-fertilize between individuals, usually using unspecialized pollen carriers or wind. As a consequence, seeds produced by any one plant can be very genetically diverse.
7. Weeds may produce more than one seed crop per year. Individuals can produce tens of thousands of seed in a given year.
8. Reproduction, particularly for perennial weeds, may include both sexual (floral) reproduction, but also asexual reproduction from roots and/or rhizomes.
9. Weeds may have highly effective seed dispersal mechanisms, from wind (dandelion) to animals (cocklebur).

Life Cycle

Weeds can also be classified on the basis of their life history. For instance, knowing whether a plant is an annual, biennial, or perennial can help weed scientists determine where a weed could become a problem.

An annual is a plant that completes its entire life cycle (from seed germination to seed development) in less than 1 year. Annuals grow quickly, and many are prolific seed producers. Summer annuals germinate in spring, grow in summer, flower, and die with the onset of frost in the fall. Examples of summer annual weeds include velvetleaf, pigweeds, and foxtail grasses. Winter annuals, in contrast, germinate in fall or early winter, flowering and maturing in spring or early summer of the following year. Examples of winter annual weeds include chickweed, shepherdspurse, and cheatgrass.

Biennials, as the name suggests, are plant species that complete their life cycle over a 2-year period. These species typically form a vegetative rosette during the first year of growth, become quiescent over winter, and then bolt during the following spring, forming a tall

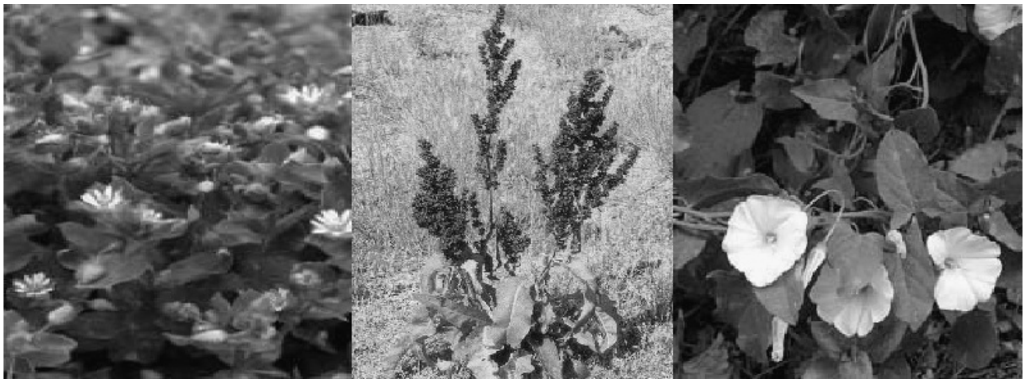

Figure 1.2 Chickweed, curly dock, and field bindweed as common examples of annual, biennial, and perennial weeds.

inflorescence with prodigious seed development. Examples of biennials include curly dock, garlic mustard, bull thistle, and musk thistle.

Among the most damaging of weeds are perennials, those that are long-lived, multi-year plant species. These can be divided into two subgroups: simple and creeping (Zimdahl, 1993). Simple perennials reproduce and spread primarily by seed, whereas creeping perennials can spread by both sexual (i.e., seeds) and asexual (i.e., rhizomes and roots) means. Examples of simple perennials would include common lawn weeds such as dandelion or plantain, or weeds of wet damp locations such as curly dock. Creeping perennials include weeds associated with contact dermatitis such as poison ivy (rhizomes and stems), and common weeds in pastures such as leafy spurge (rhizomes) and Canada thistle (roots) (Figure 1.2).

Classification by Physiology

Differences in photosynthetic pathway provide another means to classify weeds. This type of classification will also be important when we examine ongoing increases in atmospheric carbon dioxide associated with climate change in later chapters.

Initial investigations of how plants acquire carbon led to the discovery that one of the first products of photosynthesis was the production of phosphoglyceric acid, a three-carbon compound (Calvin, 1949). For the vast majority (approximately 95%) of plant species it was discovered that this type of photosynthesis (termed C_3 because the first stable product had three carbons) was the sole means by which carbohydrates were synthesized from light, energy and water. However, in the 1960s, researchers discovered other photosynthetic pathways, most notably the C_4 pathway, where the first products of photosynthesis are four-carbon sugars such as oxaloacetate, malate, and aspartate. Although these C_4 plants, principally tropical grasses, constitute only about 4% of all plant species, a higher percentage of this type of photosynthesis appears to occur among the world's worst weeds (e.g., Holm et al., 1977). A third type of photosynthetic pathway, crassulean acid metabolism or CAM, occurs in less than 1% of plant species. While succulent species use CAM photosynthesis, major weeds do not.

Classification by Habitat

One of the most well-recognized habitats for weeds is cropland. However, because crops cover a wide range of different environments, there may not be a specific set of characteristics associated with crop weeds per se. Interestingly, the most competitive weeds in a given cropping situation are often simply “imitators” or wild relatives of the crop. They are selected for by cultural practices such as planting date, fertilizer application, selective herbicide usage, etc. which while favoring the crop, also select for those weeds that are closely related physiologically, morphologically, or phenologically. Examples of crops and their weed relatives include potatoes and nightshade (both in the genus *Solanum*), rice and wild or red rice, sorghum and shattercane (both *Sorghum bicolor*), oat and wild oat.

Rangelands constitute those land areas characterized by grassland and shrubland used (although not exclusively) for animal grazing. Because of their use, classifications in rangelands are associated with those weeds whose presence is either directly (e.g., poisonous) or indirectly (competes with desired grasses) harmful to large animal (sheep and cattle) grazing. Examples of typical rangeland species include leafy spurge and yellow starthistle.

Forests have another unique set of weed species associated with them. James Miller of the U.S. Forest Service has identified over 33 plants or groups that are spreading rapidly through southern forests (Miller, 2003). As might be expected, vines that compete directly for sunlight such as kudzu, Oriental bittersweet, or English ivy are considered among the worst nonnative vines, but other perennial weeds such as Chinese and Japanese privet, nonnative roses, and sacred bamboo are also among the worst forest weeds. In addition, certain tree species can also be considered weeds and among these, nonnative trees such as Princess tree and tree of heaven are considered common weeds in forest environments.

Riparian weeds are those species that are found in wet, poor drainage areas. They are adapted to anaerobic soils and may rely on water as a means to spread by seed or asexually. Riparian weeds include purple loosestrife, curly dock, giant reed, or salt cedar.

Aquatic weeds are those weeds adapted to living directly in the water. They can be floating, submersed, or immersed (submersed but with a root system). They can reduce water quality and water supply as well as pose problems for navigation or power generation. Some of the most prevalent aquatic weeds include water hyacinth and hydrilla (Figure 1.3).

A Few Basic Principles of Weed Ecology

Weed ecology is that aspect of weed biology that studies weed distribution, growth, development, reproduction, and population dynamics of weed species in managed (human) and unmanaged (natural) plant communities.

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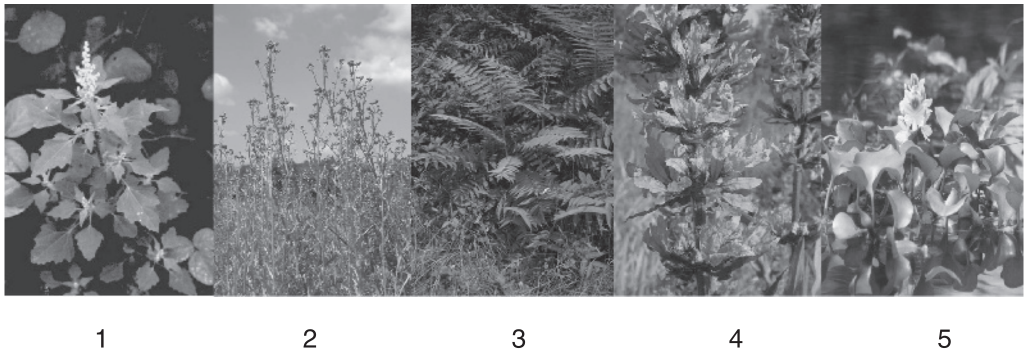

Figure 1.3 Weeds by habitat: (1) common lambsquarters in a soybean field; (2) Canada thistle as a rangeland weed in South Dakota; (3) tree of Heaven, a common weed in urban areas; (4) purple loosestrife, a common riparian weed in marshes; (5) water hyacinth, a common aquatic weed. (Photos are all from USDA-ARS Image Gallery.)

Seed Biology

We can begin with seed, and an appreciation of the ability of weeds to produce them. The number of weed seeds present in soil can be enormous. Koch (1969) has derived figures that indicate between 30,000 and 350,000 weed species per square meter (or 300 million to 3.5 billion seeds per hectare). An estimate of the number of seeds produced for a single weed can be in the hundreds of thousands (Table 1.1).

What is the fate of seed once it enters the soil? Harper (1977) envisioned the soil as a seed "bank" in which "deposits" or "withdrawals" are made. An example of a deposit would be seed rain, whereas withdrawals (seed removal) would occur by germination, deterioration, or predation. The concept of a seed bank is a very useful one for weed ecology since it provides key information regarding seed diversity and longevity as well as long-term information as to efficacy of weed management.

Seed longevity in turn, will depend on a number of factors and their interaction. Obviously, how much seed a given species produces is an important consideration as is soil type. However, seed decomposition, predation, and dormancy/germination are also key considerations. Overall, observations indicate that while seeds from grass and crop species are rarely long-lasting within the seed bank, weed seeds may last for hundreds of years if not millennia (Odum, 1965).Weed seeds are almost always present in the soil.

Seed germination and emergence is dependent on dormancy. Although there is a recognized physiological aspect of dormancy (seed ripening), most dormancy is imposed by the environment. Dormancy, in turn, can be broken by a given environmental factor or combination of factors, usually those that occur in seasonal cycles. For example, freeze/thaw combinations may be necessary to remove seed coat restrictions. Alternatively, many weed seeds need light (Sauer and Struik, 1964), which is usually abundant following a physical disturbance in the environment.

Table 1.1 Seed production (per plant) and qualification (+ or −) as to the presence of asexual reproduction for selected weed species.

	Seed	Asexual	Comments
Canada thistle (*Cirsium arvense* [L.] Scop.)	530–5,300	++	Extensive below ground root system 3 m horizontal and vertical lengths
Common lambsquarters (*Chenopodium album* L.)	9,000–370,000	−	Prolific seed producer
Common mullein (*Verbascum thapsus* L.)	200,000–300,000	−	Prolific seed producer
Common ragweed (*Ambrosia artemisiifolia* L.)	3,000–5,000	−	Agronomic weed and public health issue
Dalmation toadflax (*Linaria dalmatica* L. [Mill])	up to 500,000	++	Extensive deep root system
Diffuse knapweed (*Centaurea diffusa*)	up to 18,000	−	Not asexual, but can regrow from cut crown
Field bindweed (*Convolvulus arvensis* L.)	25–300	++	Extensive rhizome growth and establishment of large colonies
Musk thistle (*Carduus nutans* L.)	up to 100,000	−	Normally biennial, can be annual with warmer temperatures
Perennial sowthistle (*Sonchus arvensis* L.)	up to 13,000	++	Can spread extensively by roots
Purple loosestrife (*Lythrum salicaria* L.)	up to 3,000,000	−	Can regrow from woody rootstock if shoots are cut
Quackgrass (*Elymus repens* L.)	up to 8,000	++	Extensive rhizome production, can form large colonies
Wild oat (*Avena fatua* L.)	200–700	−	Common weed in cereal production
Yellow starthistle (*Centaurea solstitialis* L.)	up to 150,000	−	Can regrow if shoots cut

Reference : www.invasive.org.

Seed germination is associated with rapid metabolic activity, radicle emergence, and then shoot appearance. Germination is a perilous ecological proposition, and natural selection has caused the timing of germination to coincide with favorable environmental conditions (Probert, 1992). However, even with such selection, given the large seed populations of some weed species, it is evident that many of them fail to germinate, decompose, or get eaten.

What then are "favorable environmental conditions" that promote weed seed germination within the seed bank? Whether human or natural, any disturbance exposes soil to light, alters water and temperature regimes, and, assuming temperatures above thermal limits, can allow seeds to break dormancy and germinate. As we have seen, weeds can be a primary constituent of the seed bank; such physical (abiotic) disturbances are therefore a key factor in their establishment within the plant community.

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Emergence and Competition

Given physical disturbance of the soil as a signal for extensive seed germination, what factors following emergence from the soil are associated with weed species success? What, in other words, makes some weeds more competitive than others?

It is difficult to provide a complete answer to these questions, and scientists are still addressing many aspects of competition. However, in general, success at competition reflects the ability of a given species to acquire a limited set of resources at a greater rate than its neighbors, whether those neighbors are a different species (interspecific competition) or the same species (intraspecific competition). How these resources are acquired depends on both genetic hard-wiring (e.g., rate of leaf development, nitrogen use efficiency, etc.) and spatial and temporal variability of physical resources (e.g., nitrogen distribution in the soil, rainfall, temperature, etc.). In general, plant competition is for abiotic resources, principally light, water, and nutrients between or within species.

Because light varies in duration, intensity, and quality, and must be used immediately or lost permanently, those plants that intercept light and shade their neighbors are at a competitive advantage. Plants invest heavily into new leaf formation, particularly after emergence. Indeed, a simple comparison of leaf area ratio among seedlings can be used as one measure of early competitive success between weeds and crops (Kropff and Spitters, 1991). However, too much investment in leaves at the expense of stems or branches may also result in a disadvantage, since height is an important consideration in light interception. Overall, in many cropping situations where water and nutrients may be nonlimiting, light competition may be one of the principal factors influencing weed–crop interactions (Donald, 1961) and reducing crop productivity (e.g., oat and wild oat; Cudney et al., 1991).

Water availability varies greatly by region, and competition for water among seedlings can be severe in areas where natural rainfall is low or inconsistent (e.g., rangelands and savannah). Less competition is usually associated with irrigated systems, although variation in delivery times and water quality (e.g., salinity) may be an additional feature related to competitive success. Overall, there are three factors associated with competition for water as suggested by Radosevich et al. (1997): (a) variation in the total amount and temporal availability of water inputs into the soil; (b) soil volume available to the plant, i.e., the rate of root development and exploration of that volume; and (c) physiological factors related to the exchange between carbon acquisition and water loss. For some weedy species, rapid depletion of available water may be an effective strategy for competition with crops (e.g., cocklebur and soybean; Scott and Geddes, 1979); alternatively, a number of common weedy species have the C_4 photosynthetic pathway, which increases overall water use efficiency (the ratio of CO_2 uptake to H_2O loss) and may be at an advantage within the plant community if water becomes limiting. In general, success in competition for water will be dependent on the relative abilities of the individual species to obtain the resource and to tolerate water deficits (Table 1.1; Patterson, 1995).

Nutrients are a recognized environmental resource needed for plants to complete their life cycle. Nutrients are divided into two broad categories based on the relative needs of the plant, namely, macronutrients (those needed in large amounts), such as carbon,

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oxygen, hydrogen, nitrogen, potassium, calcium, phosphorous, magnesium, and sulfur; and micronutrients (needed in lesser amounts) such as iron, chlorine, copper, manganese, zinc, molybdenum, and boron. Competition for these nutrients is both dynamic and complex since nutrient availability is dependent on soil characteristics, most notably pH, and aspects of plant morphology such as root development, that are species specific (Patterson, 1995). It is difficult then to predict a precise competitive outcome for an explicit nutrient deficiency. Nevertheless, there are some generalizations that can be made. First, it is clear that weeds utilize nutrient resources at least as rapidly as many crop species. This suggests that weed removal should result in greater nutrient availability to the crop species. Second, there is evidence that weeds may be more efficient at removing nutrients from the soil than cultivated plant species (Vengris et al., 1955).

The previous examples are meant to be illustrative, and are by no means a complete synthesis of what is known regarding competition. For example, while nutrients, water, and light are presented as individual physical limitations, it is common for one or more to be limiting simultaneously. In addition, most competition experiments have focused on suboptimal conditions, not on circumstances where such factors may be in excess (e.g., flooding and agronomic fertilization). Yet, differential responses to an overabundance of resources may also have significant implications for plant–plant interactions.

Weed Reproduction and Spread

Having examined how weeds survive in the seed bank, germinate, emerge, and compete successfully, we can turn our attention to reproduction and distribution within the environment. How do weeds become distributed in the environment?

One reproductive method, common among many perennial weeds, is through vegetative or asexual reproduction. Vegetative portions of the plant capable of regeneration include stolons, long, slender stems that grow parallel to the soil surface (e.g., Bermuda grass); rhizomes, stems that grow underground, while producing adventitious roots and shoots (e.g., quackgrass and poison ivy); tubers, which are extensive belowground storage organs (enlarged rhizomes) that possess axillary buds (e.g., Jerusalem artichoke); bulbs, modified underground buds capable of regeneration (e.g., wild garlic and wild onion); corms, enlarged underground perennial stems for carbohydrate storage (e.g., wild onion); and roots (usually horizontal that can give rise to separate shoots (e.g., Canada thistle and field bindweed). Although many perennials do produce vegetatively, most, if not all, also reproduce sexually through flowering. Hence, such weeds can maintain both a high density of individuals for a given surface area, as well as spread via seed dispersal. It is important to distinguish the seed bank and the presence of vegetative bud reserves since both are an aspect related to establishment, dominance, and competition from the soil. In general, buds are representative clones from a single plant, whereas the population of buried seeds represents a broader range of genotypes. Consequently, vegetative reproduction should be at an advantage when environmental conditions are stable, whereas seed genotypes would be favored with continuous disturbance. This would suggest that after a soil disturbance, seed genotypes would dominate

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initially, followed by the appearance of herbaceous perennial weeds with high vegetative bud reserves. Such vegetative reserves can be impressive. For example, within 2 years, Canada thistle plants can produce over 66 feet (20 m) of new roots (Parsons, 1992).

Getting the Seed Out

As we have already observed, one of the characteristics of weed species is prodigious seed production. However, widespread distribution of these seeds, through a wide array of vectors, aids in their spread and negatively impacts their control.

A number of weed species have plumed seed for wind dispersal. These include dandelion, Canada thistle, mare's tail, and a number of weeds within Asteraceae. The plume, or pappus, is the "parachute" used for wind dispersal, with the extent of wind displacement related to the ratio of seed weight to pappus size. That is, those species that produce a low ratio of achene diameter to pappus size have higher "hang-time" and can disperse farther from the mother plant. Plant size, particularly the height of seed release, is also positively correlated with area of dispersal. Tall plants (those over 1 m in height) can distribute seed as far as 5 km (Dauer et al., 2007) depending on wind velocity and degree of infestation. In addition to disseminating seed directly, wind can also move senescent or detached portions of a plant, with subsequent distribution of seed over a wide area. For example, tumbleweeds such as Russian thistle can travel several kilometers while dispersing 60,000 seeds per plant (Stallings et al., 1995).

A number of weed seeds without any special morphological modifications can travel by water. This is a particular concern in agricultural areas where irrigation is common. An early study by Eddington and Robbins (1920) found a total of 81 different weed species in irrigation ditches in Colorado. A study done by Wilson (1980) found a total of 77 different plant species in three main irrigation canals over two seasons, collecting a total of 30,346 seeds. Interestingly, many weed seeds are able to survive long periods of time submerged in water. For example, seed of field bind weed had 55% germination, even after 54 months under water (see Table 5.3; Zimdahl, 1993). Water then, can be an effective means to distribute weed species over a large geographic area.

Many weed seeds are characterized by having various hooks and/or barbs on the seed coat (e.g., puncturevine and cocklebur). Others may possess a sticky coating or resin (e.g., gumweed). These features are commonly associated with mechanical dispersal of weed seeds by animals. Spread of some weed species in the western United States, for example, can be traced to grazing areas of sheep and cattle (Crafts, 1975). In addition to such mechanical dispersal, animals may also distribute seed directly by ingestion followed by partial digestion. After passing through the alimentary canal, seed can then be spread via feces. Harper (1977) and King (1966) provide a number of examples of seed dispersal by birds, rodents, and wild and domesticated ruminants. Bird distribution in particular can move seeds over thousands of miles (Proctor, 1968).

Human activities, particularly in agriculture, are a well-recognized vector in weed seed dispersal. Farm machinery, such as plows, harrows, and even tires can spread weed seed well beyond its original source. Farming practices influence which weed species become established. For example, in rice farming, direct seeded rice is associated with the spread of wild or "red" rice because the seed of red rice is often indistinguishable from that of the cultivar. Conversely, rice that is transplanted into flooded conditions is associated with weeds that are tolerant of such wet or paddy environments such as *Echinochloa* species.

In addition to farming practices, the globalization of trade has also resulted in the introduction of numerous "exotic" or "invasive" weed species. For example, Japanese stiltgrass, a forest understory weed, was introduced as packing material into Tennessee in the early twentieth century (Fairbrothers and Gray, 1972); cheatgrass may have been introduced as a contaminant with crop seed (Novak and Mack, 2001). Introduction of other weedy species has been deliberate because their initial introduction was thought to be of economic benefit. Perhaps the most notorious example is kudzu, a leguminous perennial vine; now spread over 8 million acres in the southeastern United States, whose properties as forage and feed for cattle attracted the attention of the USDA, which heavily promoted the planting of kudzu as late as the 1940s.

The Harm that Weeds Do

So far we have discussed a number of principles that can be used to characterize weeds and their ecology. This may seem like a pointless exercise, since many people do not consider plants to be "bad." However, it is important to acknowledge the harmful nature of weeds and to recognize that "green" is not always good.

Food

Agriculture is the principal provider of food for the human population. Of the 250,000+ plant species on Earth, only a few species have been able to be specifically cultivated for human consumption, and of those, three cereals, rice, wheat, and corn supply the global population with approximately 50% of their calories. Overall, more than 90% of the population is supplied by less than 20 plant species (Diamond, 1997). Although one can argue the benefits of modern agriculture (ability to feed large numbers with small amounts of land) versus its detriments (large inputs of fertilizer and water contaminants), there is no question that the current population of the world (6.9 billion) is very much dependent on modern agricultural techniques and the maintenance of high crop yields.

Any impediment on these yields therefore has enormous implications for the ability of a region or country to provide sufficient food for its population. The three major biological barriers to maximal crop yields are insect pests, weeds, and plant pathogens. Among these, weeds are the largest limitation to maintaining crop yields. There are many times more weed species than crops; for example, in the United States, there are approximately 10 weed species that compete with each crop species (Bridges, 1992).

Weed/crop competition is a major factor limiting food production worldwide. For example, in China 10 million metric tons of rice is estimated to be lost annually due to weed competition (Zhang, 2001), enough rice to feed 56 million people for 1 year (Labrada, 2007).

In addition to their direct effects on reducing crop yields, some weeds host damaging insects or pathogens. Tall morning glory, for example, is a host for leaf blight, cocklebur for stem rust; insects such as the corn borer may use Russian thistle as a means to spread curly top. Other weeds may be hosts for different nematodes that damage soybean and corn.

While negatively impacting yields, weeds may also affect quality. The presence of wild oat or red (weedy) rice can reduce milling quality of rice and wheat flour, and can reduce brewing quality for beer. The presence of weeds within forage crops such as hay can also reduce both the protein concentration and the economic return for growers.

Negative effects of weeds on pasture and forage crops can also reduce animal quality. In western rangelands, some widespread weed species such as larkspur, leafy spurge, and yellow starthistle are poisonous or do direct physical damage to animal grazers. Such damage is considerable. For example, it has been estimated that leafy spurge reduces the livestock carrying capacity of pasture and rangeland by 20–50% with a subsequent loss of $35–45 million in U.S. beef and hay production (Bangsund and Leistritz, 1991).

Water

Many aquatic weeds complicate water utilization and management. Pervasive water weeds such as hydrilla (water thyme) in the southeastern United States and water hyacinth and common coontail globally can form large mats that interfere with transport of irrigation water and cooling water for hydroelectric plants. Such weeds may also interfere with recreational activities such as boating or fishing. Riparian weeds may also be heavy users of water, with a subsequent strain on water availability (Anderson, 1982). For example, salt cedar invasions in riparian areas of the southwestern United States are often blamed for depleting freshwater resources needed for irrigation or urban centers (although there is some controversy surrounding this point; Shafroth et al., 2005; Figure 1.4).

Environmental Damage

Some weeds may colonize a given habitat so successfully that native species may be eliminated altogether, with a subsequent decline in species diversity. Such weeds, usually nonnative for a given system, have proliferated to such a large extent that they are recognized by a separate classification; invasive or exotic weeds. Their introduction, commonly by human transport, results in widespread economic or environmental damage (Mooney and Hobbs, 2000). An example of the type of environmental damage related to the introduction of these invasive weeds is alteration of the fire cycle within native plant communities. These cycles are, in turn, accelerated by the introduction of fire-tolerant grass species such as cheatgrass, that can produce combustive vegetative with subsequent increases in the frequency, spread, and intensity of natural- or human-induced fire (Brooks et al., 2004). The conversion of shrub-dominated steppes of the western United States to a cheatgrass-dominated landscape during the twentieth century is a quintessential example of how invasive species introduction can significantly alter plant community composition over a large geographic area.

Cheatgrass is not the only species having dramatic effects on the landscape (Dukes and Mooney, 2004). Millions of acres of productive rangelands, forests, and riparian areas have been overrun by weedy invaders, with a subsequent loss of native flora. The proliferation

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Figure 1.4 Salt cedar as a threat to water flow in the western United States. Accumulation of salt by this species may also alter soil salinity with negative effects on native plants. (John M. Randall, The Nature Conservancy.)

of aquatic weeds, in turn, can lead to greater eutrophication and significant disruptions in marine biology. It has been estimated that more than 200 million acres of natural habitats (primarily in the western United States) have already been lost to invasive, noxious weeds, with an ongoing loss of 3,000 acres a day (Westbrooks, 1998). The invasive plant species that are most harmful to native biodiversity are those that significantly change ecosystem processes (e.g., cheatgrass) to the detriment of native species.

Public Health

While the interaction of weeds and public health may seem somewhat obscure, weeds can directly affect public health through allergenic reactions, skin irritations, mechanical injury, and toxicology. Current estimates suggest there are approximately 30 million plant-based allergy sufferers in the United States. While many of these people are allergic to pollen of ornamental trees and grasses, a common weed, ragweed (*Ambrosia* spp.) is the principal source of plant-based allergens in the fall. A different kind of allergy, contact dermatitis or a skin-based allergic reaction, is also associated with weeds. Some examples include the milky sap in spurges or giant hogweed, stinging nettles, or urushiol contact with the poison ivy group. In the latter case, it is estimated that over 2 million people in the United States suffer annually from casual contact with poison ivy, poison oak, or poison sumac (Mohan et al., 2006).

Mechanical injury associated with weeds, from unwittingly removing a Canada thistle plant by hand to stepping barefoot on puncturevine seeds, can be a painful, although nonfatal

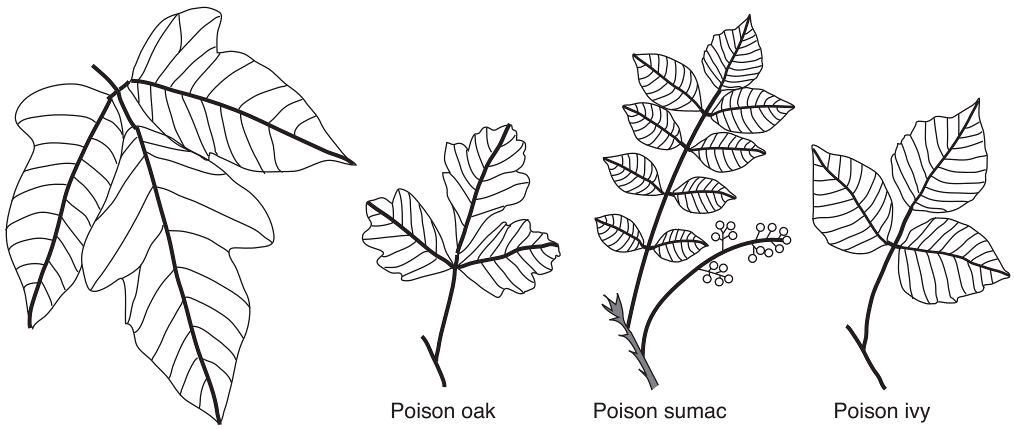

Figure 1.5 Poison ivy, a common weed of disturbed sites and contact dermatitis from poison ivy. (From USDA NRCS plants database.)

experience. Ingestion of poisonous weeds, however, can result in serious illness or death. There are over 700 plant species that are known to induce illness in humans or livestock. Some weed species such as poison hemlock, nightshade, or castor bean are so poisonous that even small quantities can be lethal. For example ricin, the poison contained within castor bean, has been linked to terrorist threats, in part, because ricin has a greater potency than cyanide (Figure 1.5).

There are other, more indirect means by which weeds impact human suffering. If weeds are unwanted plants, then plant-based sources of narcotics, from coca to poppy should be considered a significant threat to public health. Weeds may also indirectly alter air quality. Kudzu, for example, emits isoprene, a chemical precursor leading to tropospheric ozone formation (Sharkey and Loreto, 1993). Weeds can also affect the prevalence of human disease by providing food sources for disease vectors. Pollen, for example, can serve as a food source for mosquito larvae (Ye-Ebiyo et al., 2000), with potential interactions between mosquito populations and weed pollen.

Aesthetics

Aquatic weeds do not just interfere with water delivery, but detract from our enjoyment of the pleasures of nature, such as swimming in a clear lake. Avid gardeners spend many hours removing dandelions, chickweed, carpetweed, and garlic mustard because those plants take away from the colorful design the gardener wishes to create. Lawn enthusiasts also spend many hours (and many dollars) in cultivating a uniform green sward. And, as any home-owner can tell you, weeds can reduce property values. Yet, how can one quantify these impacts? Aesthetical deterioration of the environment is universally recognized, but remains ill-defined.

Figure 1.6 Examples of weed control: (1) Dr. John Teasdale, USDA-ARS weed scientist examines hairy vetch as potential cover crop in cultural weed control; (2) mechanical weed control through conventional tillage in soybean; (3) use of herbicides in no till field crop; (4) Dr. Rick Bennett, USDA-ARS Plant Pathologist, examines fungi that could be used for biological weed control. (Photos are USDA-ARS Image Gallery.)

Weed Management

Given the damage that weeds do to human activities, to the environment, and to public health, weed management remains, even today, the principal focus of weed science. Management, in turn, can be defined as those practices used to restrict the growth and spread of weeds. In general, these practices focus on three main areas: prevention, eradication, and control.

Prevention refers to those actions taken to inhibit the introduction and/or establishment of weed species into new areas. Eradication is defined as a set of measures taken to completely remove a weed species from an area. However, complete eradication is rarely achieved, in part, due to the high cost and effort involved in eliminating a weed species, particularly if that species has spread over a wide ($>$10 ha) area. Control is the more achievable outcome once a weed has become established, and refers to those methodologies that can reduce (but not eliminate) weed impacts to manageable levels. There are four recognized methods of weed control: (1) cultural, (2) mechanical, (3) chemical, and (4) biological (Figure 1.6).

Cultural

Cultural control recognizes and optimizes those practices common to good land and water management. At the farm level, these may include using weed-free crop seed, crop rotation to reduce the accumulation of high weed populations of certain species, and the use of smother crops or living mulches such as hairy vetch to control weed seed emergence (Teasdale and Mohler, 1993).

Mechanical

Mechanical control reflects some of the oldest known means to eliminate weed populations, including hand-pulling and hoeing. However, mechanical may also refer to flooding, a typical means of weed control in rice cultivation since rice can survive flooded conditions and many

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weeds cannot; the use of nonliving material to mulch the soil, usually as a means to prevent light interception from emergent weed seedlings; flaming or burning, utilizing controlled fire to burn young succulent weeds; and machine tillage, such as the use of chisel plows, weed knives, disc harrows, or some other tractor implement that breaks the soil and buries the weed.

Chemical

By far in the United States, and in most developing countries, chemical control of weeds through the selective application of herbicides is the most utilized practice. If applied properly and with respect to their utilization and safety, herbicides have been the most effective means to control weeds and to limit their negative impacts, particularly in crop production systems. For example, it has been estimated that in the United States, under best management practices, production losses associated with weeds averaged between 7 and 10%; however, without herbicides, those losses were between 35 and 38% (Bunce and Ziska, 2000; Table 1.2).

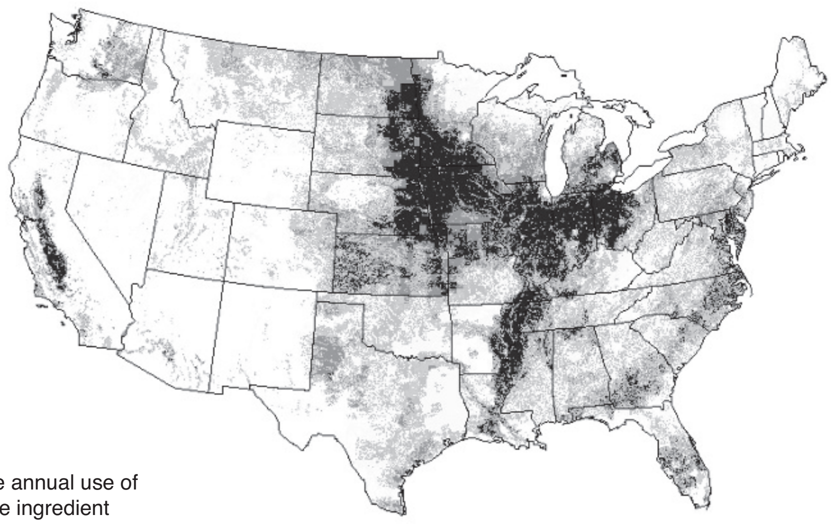
In 2002, approximately 78,000,000 ha of land in the United States was chemically treated to control weeds, grass, or brush; for comparison, 34,000,000 ha were treated chemically for disease, nematode, and insect control *combined*, for that same year (National Agricultural Statistical Service, www.nass.gov; Figure 1.7).

Because of their importance, many weed science texts are written specifically to address herbicide chemistry, focusing on physiological responses and a systematic evaluation of application methods that can increase uptake and overall efficacy of the herbicide. Such detail, however, is beyond the scope of this book, and we refer interested readers to excellent books by Duke (1985) and Monaco et al. (2002).

Table 1.2 Estimated production losses due to weeds for selected crops in the United States.

Crop	Best management practices ('000 Mt)	Best management practices without herbicides ('000 Mt)
Barley	261 (5)	1,045 (20)
Corn	19,967 (6)	99,837 (30)
Cotton	349 (8)	2,139 (49)
Potato	1,219 (6)	5,890 (29)
Rice	628 (7)	4,847 (54)
Sorghum	1,033 (8)	4,519 (35)
Soybean	5,838 (8)	27,731 (38)
Sugarcane	2,452 (9)	10.081 (37)
Wheat	3,382 (6)	11,273 (20)
Total	*35,129*	*167,362*

Production loss percentages (in parentheses) were calculated from data in Bridges (1992) and applied to 2007 production figures. Average crop losses due to weeds were 7% for best management practices and 35% for best management practices but without herbicide. Production values for sugarcane refer to bulk cane production.



Crops	Total pounds applied	Percent national use
Soybeans	70,699,653	69.49
Corn	7,491,973	7.36
Cotton	7,063,492	6.94
Wheat for grain	3,509,151	3.45
Cropland in summer fallow	2,514,196	2.47
Citrus fruit	2,186,741	2.15
Sorghum	1,596,879	1.57
Rice	1,057,534	1.04

Figure 1.7 Estimated annual usage of glyphosate, the most frequently used herbicide in the United States. (From 2002, USGS pesticide use maps.)

In brief, herbicides are phytotoxic, usually organic compounds, divided into chemical families which include aliphatic and aromatic carboxylic herbicides, the substituted urea, carbamate, dintirophenol, dinitroaniline, *s*-triazine groups as well as the phosphonate/organic phosphorous compounds such as glyphosate. Nonorganic herbicides may include salts (e.g., copper sulfate) as well as acetic acid. Herbicides can be either selective or nonselective regarding the type of plant targeted, and may or may not travel to the site of action (i.e., systemic). Herbicides are either applied directly to emerged plants (postemergence) or directly to the soil (preplant or preemergence). Application of the herbicide may be as a spray in water or oil, or as dry granules. Added surfactants such as soap often increase absorption of the active ingredient by the plant.

Biological

Biological control is a strategy to employ a specific organism (parasite, predators, and pathogen) that once introduced will provide a measure of weed control, usually specific to the weed species. Biological control, if successful, can result in permanent weed control because the controlling organism is self-perpetuating. Another advantage is that the controlling organism, if benign, does not contribute to environmental pollution.

There are, however, a number of cautionary hurdles that must be overcome if biological control is to be effective. If the weed to be controlled is unwanted in one area, but valued in another, and both areas are within the same geographical region, biological control should not be used. Introduction of the biocontrol agent must be specific to the organism to be controlled and introduction of the controlling organism should not pose an additional environmental threat (e.g., cane toads introduced to Australia for biological control have become an enormous problem in themselves). The organism must tolerate similar environmental conditions as the weed species it is directed against, so it can survive in the same range. Overall, to produce an effective biocontrol measure requires money, time, and much effort on the part of the research community.

Integrated Pest Management

Integrated pest management (IPM) is not a single control measure per se, but an amalgamation of available means to monitor and control all pests (weeds, diseases, and insects) (Flint and van den Bosch, 1981). The driving force behind IPM was to develop a synergistic approach to monitoring and controlling pest populations. Overall, IPM is organized around six basic tenets:

1. Determination of acceptable pest levels, with the focus on control rather than eradication.
2. Use of cultural practices as previously described, in order to maintain healthy plants selected for a specific growing environment.
3. Monitoring of background pest levels. Regular observation is a fundamental principle of IPM. Visual inspection, traps, and other observational methods are employed to establish a history of potential pests for the region.
4. Mechanical control as a first line of defense. If a pest(s) reach unacceptable levels, mechanical options such as hand-pulling or tillage are utilized.
5. Chemical control as required. Emphasis on the use of chemicals as necessary and application of these chemicals at the most optimal time for successful weed control (e.g., greater efficacy of herbicides applied when weeds are in the seedling stage). The use of organic products in the field with limited environmental carryover whenever possible.
6. Development of long-term nonchemical solutions such as biological control.

Summary

It is impossible to summarize all that is known regarding weeds in a single chapter. It is hoped that the themes introduced here will provide an overview of the key aspects of weed biology, particularly how they are defined, characterized, and classified; the basic principles of weed ecology, focusing on the steps from seed germination to seed production; an overview of the negative impacts weeds have, both in human society and in nature; and, lastly but perhaps most importantly, methods of weed control by which these impacts can be minimized. In the following chapters, we will explore these themes in more detail, particularly in the context of anthropogenic climate change, the subject of our next chapter.

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