

Bhagirath S. Chauhan · Gulshan Mahajan  
*Editors*

# Recent Advances in Weed Management

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 Springer

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# Preface

Agriculture will remain the mainstay to feed the teeming millions in the years to come, which is indeed a tremendous and tough task. The untiring efforts and unflinching zeal of research scientists have transformed agricultural production from mere sustenance into commercial farming. An influx of technologies has transformed the very outlook of the farmers who look toward scientists for support in diverting their farming into profitable enterprises. Efficient weed management approaches are expected to contribute significantly in sustaining and increasing the profitability of agriculture. Advanced research in weed science provides knowledge to the weed science community in formulating research planning as well as developing guidelines for the farmers to save their crops from the menace of weeds.

Weed problems have turned into a continuing struggle for farmers on account of pressure to raise crops and increasing their productivity to meet the ever-growing demands of a fast-growing human population. As per the requirements of various crops, starting from hand weeding, weed control has gone through a number of changes with the advent of new technologies. Herbicide use is increasing globally as agriculture labor is becoming not only scarce, but also costly and not available at the right times. The growth of chemical weed control is attracting scientists and industries to work on herbicides that are eco-friendly and required in low doses. The new molecules that can be used in small quantities help in reducing the herbicide load in the environment, but may create some residue problems and pose high selection pressure. Research, therefore, is now focused on new methods of weed control, such as the use of cultural, biological, and biotechnological approaches that could be integrated with chemical weed control to reduce the herbicide load in the environment.

In this book, an attempt has been made to highlight the emerging weed management issues and to suggest measures to tackle these issues through advanced methods of weed control and better understanding of the ecology and biology of weeds. The authors of each chapter of this book were invited to contribute based on their experience and respective areas of expertise. To our knowledge, no book exists that summarizes the advanced methods of weed control to handle the emerging issues of weed science, and that too in the current changing scenario.

In this book, the thrust areas requiring immediate attention of weed scientists are covered: biology and ecology of weeds, new challenges in weed science and

research priorities, development of resistance to herbicides in weeds, control of aquatic and parasitic weeds, weed management in conservation agriculture, role of allelopathy in weed management, and integrated approaches for weed management in important crops. Through this book, the message has been given that to make an integrated weed management program a success, it would require improved information and technical assistance to growers in choosing correct methods for controlling the complexes of weeds. The main goal of this book is to provide comprehensive knowledge that will enable the weed scientists and policy makers—in careful planning, designing, and orientation of research and development of weed management—to ensure sustainability in agriculture. We expect that this book will provide sound guidelines for future weed management strategies to boost agricultural production by allowing the readers to benefit from the collective experience of others instead of learning through “the hard way.”

Bhagirath S. Chauhan  
Gulshan Mahajan

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# Chapter 1

## Ecologically Based Weed Management Strategies

Bhagirath S. Chauhan and Gurjeet S. Gill

### Introduction

Weeds are one of the most important biological constraints in agricultural production systems. They negatively affect crop growth and yield by competing with crops for nutrient, sunlight, space, and water. In some regions, especially in developing countries, weeds are controlled by using hand weeding. However, manual weeding is becoming less common due to labor scarcity on farms and high labor wages [1]. In other regions, herbicide use has allowed a massive release of labor from agriculture [2]. The increased use of herbicides, however, has been accompanied by concerns over the evolution of herbicide resistance in weeds, weed species population shifts, increased costs of herbicides, surface-water pollution, and effects on nontarget organisms [3–5]. Therefore, a heavy reliance on chemical weed control is considered objectionable in some regions [6, 7]. Water, as flooding, is used to manage weeds in crops such as rice (*Oryza sativa* L.). However, farmers in many areas, especially in Asia, are expected to experience economic and physical water scarcity [8], which may make it unfeasible for them to flood rice fields to ensure sufficient weed control [4]. These concerns have increased the interest of weed scientists around the globe to develop ecologically based weed management strategies [4, 9–12].

To develop ecologically based weed management strategies, however, knowledge of weed ecology and biology is essential. Even in the era of herbicides, understanding the biology of weeds remains essential for developing effective weed management tactics [12]. In this chapter, we discuss ecologically based strategies to

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reduce the weed seed bank before crop sowing and to reduce weed emergence and growth in crops.

## Strategies to Reduce the Weed Seed Bank

Weed seed banks are the reserves of viable weed seeds present on the soil surface and in the soil. These are the primary source of annual weed infestation in most crop production systems [13–15]. Farmers would benefit from management practices that reduce weed seed input, increase weed seed losses, and reduce the probability that residual weed seeds establish [16]. Weed seed banks are usually depleted through germination, predation, or death. Before discussing specific strategies, there is a need to better understand the effect of light and seed coat on weed seed germination.

Light plays an important role in weed seed germination. However, the germination of different weeds in light and darkness varies [1, 15]. Seeds of some species (e.g., *Avena fatua* L., *Malva parviflora* L., and *Mimosa invisa* Mart. ex Colla) germinate equally in light and dark; seeds of some species (e.g., *Eclipta prostrata* [L.] L. and *Cyperus difformis* L.) do not germinate in the dark at all; seeds of some species (e.g., *Galium tricornerutum* Dandy) do not germinate in the light; and, for some weed species (e.g., *Echinochloa crus-galli* [L.] P. Beauv. and *Sisymbrium orientale* L.), light is not an absolute requirement for germination, but light stimulates germination [4, 17–21]. In the field, light conditions differ for weed seeds present on the soil surface, beneath the crop residue cover, or buried in the soil.

Seeds of some weed species (e.g., *Malva parviflora*, *Mimosa invisa*, *Abutilon theophrasti* Medik, *Urena lobata* L.) have a hard seed coat, which imposes dormancy due to the impermeability of the seed coat to water or gases [19, 22–25]. Germination of such seeds is generally low unless they are scarified. In some species (e.g., *Rottboellia cochinchinensis* [Lour.] W.D. Clayton and *Raphanus raphanistrum* L.), dormancy is largely due to the pod surrounding the seeds [26, 27]. Mechanisms that increase breakdown of the pod will increase germination of species with such seeds. Possible factors that may account for a dormancy break in hard-seeded species and seeds surrounded by the pod are microbial and fungi attack, changes in temperature and moisture regimes, and fire [15, 28].

## Seed Predation and Decay

One way to reduce the size of weed seed banks is through mortality of newly produced weed seeds by predators [16, 29]. Seed predation has been recognized as an important means of seed mortality, particularly after seed shed [6, 30]. Weed seeds are most prone to seed predators while on the soil surface and burial makes seeds largely unavailable to most seed predators [31]. Furthermore, weed seeds present on

the soil surface are also prone to rapid decay due to unfavorable weather conditions, such as extreme changes in temperature and moisture fluctuations [32]. Therefore, the use of no-till systems, in which most of the weed seeds remain on the soil surface, may expose weed seeds to seed predators. By delaying tillage operations or creating an additional time lapse between seedbed preparation and seeding, the first weed flush can be easily controlled [6, 33]. The number of seed predators can be increased by creating better opportunities for shelter and additional food [34]. For example, the management of field bunds, through creating favorable environments for seed predators by accumulating crop and weed residues on bunds rather than burning them, could provide a promising opportunity to encourage weed seed predation [29]. Similarly, organic cropping practices, especially cover cropping, may increase the activity of weed seed predators [16].

Different studies suggest that seed predation can cause a substantial reduction in the number of weed seeds entering the seed bank, and therefore could contribute to ecologically based weed management in different crops. Seed predation could be achieved with no additional costs, and it could easily be integrated into existing management practices, which could increase adoption by farmers.

### ***The Stale Seedbed Technique***

In the stale seedbed technique, weeds are allowed to germinate after a light irrigation or rainfall and are then killed by using a nonselective herbicide (e.g., glyphosate or paraquat) or a shallow tillage operation. As most of the weed seeds remain on the soil surface after crop harvest, this practice may help to reduce the weed seed bank. Most weed species sensitive to the stale seedbed practice are those that require light to germinate (as discussed in a previous section), have low initial dormancy, and are present on or near the soil surface. Some of these weed species are *Digitaria ciliaris* (Retz.) Koel., *Leptochloa chinensis* (L.) Nees, *Eclipta prostrata*, and *Cyperus iria* L. Therefore, knowledge about the effect of light on the germination of different weeds may help to make the decision regarding the use of the stale seedbed practice. The feasibility of this practice, however, should be assessed by farmers themselves, especially when the period between the harvest of the previous crop and the sowing of the subsequent crop is short.

### **Strategies to Reduce Weed Emergence and Growth in Crops**

Various strategies—such as tillage practices, the use of crop residue as mulch, cultivars with weed competitiveness and allelopathy, and agronomic practices aimed at early canopy closure with the use of a high seeding density and narrow row spacing—can be used to reduce weed seedling emergence and weed growth in crops.

## *Tillage Systems*

Weeds emerging in a crop can be reduced by using different tillage practices. However, the effect of tillage practices on weed emergence depends on the intensity and timing of tillage; type, speed, and depth of the tillage or seeding equipment; and the extent that the soil environment is modified by the tillage [15]. Tillage and seeding operations determine the vertical seed distribution of weeds in the soil profile, and this distribution affects weed seed germination and seedling emergence through the influence of seed predation, seed decay, seed dormancy, seed longevity, seed size, light requirement for germination, and potential of a seedling to emerge from a given depth [14, 35]. An earlier study, for example, reported that a no-till system retained 56% of the weed seeds in the top 1-cm soil layer, whereas a conventional tillage system buried 65% of the seeds to a depth of 1–5 cm and only 5% of the seeds remained in the top 1-cm soil layer [14]. In another study, about 85% of all weed seeds were found in the top 5-cm soil layer in a reduced tillage system and only 28% of the weed seeds were found in this soil layer in the conventional tillage system [36]. These studies suggest that no-till or reduced tillage systems leave most of the weed seeds on or near the soil surface. In some species (e.g., *Lolium rigidum* Gaud.), weed seeds present on the soil surface under no-till and zero-till germinate and emerge at a slower rate than seeds buried to a shallow depth by tillage. Weeds emerging later and after the crop are likely to be at a competitive disadvantage against the crop in no-till than those emerging before or with the crop under conventional tillage systems [14].

As discussed in a previous section, seeds present on or near the soil surface are prone to seed predation and decay. Therefore, adopting no-till systems for some crops may help to enhance seed predation and deplete the seed bank, resulting in fewer weed seedlings in the crop. In no-till systems, most of the weed seeds are present on the soil surface, where light may stimulate germination and help in reducing the seed bank through germination. In some situations, a large weed seed bank may accumulate on the soil surface. In such situations, a deep inversion tillage operation could be used to bury weed seeds below the maximum depth of their emergence. Most weed seedlings cannot emerge from depths more than 10 cm. A previous study also suggested that the success of *Alopecurus myosuroides* Huds. in reduced tillage systems could be overcome by plowing once every 5 years [37].

Rotation of tillage or crop establishment systems may also help to reduce weed problems in crops. In rice, for example, the built-up population of *Ischaemum rugosum* Salisb. in wet-seeded rice was reduced by using a no-till system [38]. Similarly, the increasing population of *Echinochloa colona* in no-till rice could be managed by shifting to wet-seeded rice [38, 39].

In conservation agriculture, permanent residue for soil cover has been advocated as this improves soil and moisture conservation [40, 41]. The presence of crop residue on the soil surface can also help suppress weed seed germination and seedling emergence; however, the extent of suppression depends on the quantity and allelopathic potential of the residue and the weed species [15, 42, 43]. The presence

of large amount of crop residue on soil surface can substantially reduce and delay weed seedling emergence by preventing light penetration, decreasing thermal amplitude, and increasing the time needed for seedlings to emerge through the residue cover. Crop residues may also reduce weed seed germination through their chemical effect, such as allelopathy and toxic microbial products. The Turbo seeder has been found effective in India to plant wheat (*Triticum aestivum* L.) and rice under high residue amounts because it diverts straw in front of the tines and places it in between two crop rows [44]. Straw mulch placed between the two crop rows inhibits the emergence of weeds and also adds organic matter to the soil. In a recent study in the Philippines, a residue amount of 6 t ha<sup>-1</sup> significantly reduced seedling emergence and biomass of *Dactyloctenium aegyptium* (L.) Willd., *Eclipta prostrata*, *Eleusine indica* (L.) Gaertn., and *L. chinensis* as compared to a no-residue situation in a sprinkler-irrigated zero-till dry-seeded rice system [45]. In some crops (e.g., corn [*Zea mays* L.], soybean [*Glycine max* L.], etc.), cover crops and their residues are used to suppress weeds [46, 47]. The presence of rye mulch, for example, was reported to reduce weed biomass in corn, without any detrimental effect on corn yield [48]. Therefore, integrating the use of residue as mulch with other weed management strategies could help in reducing weed pressure in crops.

### ***The Role of Cultivars in Suppressing Weed Emergence and Growth in Crops***

The use of weed-competitive cultivars and cultivars having allelopathy can help in providing supplemental weed control when herbicide inputs decrease [49]. Weed competitiveness has been investigated for several crops, such as sugar beet (*Beta vulgaris* L.), soybean, corn, wheat, and rice [50–55]. Tall and traditional crop cultivars with droopy leaves are generally more competitive, but they are often lower in yield potential than short-statured modern cultivars with erect leaves. In Australia, Vandeleur and Gill showed that there was a significant positive linear relationship between the year of wheat cultivar release and crop yield loss from weed competition, indicating the inferior competitive ability of the modern cultivars related to their shorter stature [56]. Therefore, there is a trade-off between yield potential and competitive ability. In the future, the use of nitrogen fertilizers may rise in some crop production systems to meet the increasing food demand, and high nitrogen doses are known to cause lodging in tall cultivars [1]. Therefore, by selecting traits other than tall plant type, the trade-off between yield potential and competitive ability may be minimized.

High genetic correlations between leaf area index of wheat and its yield loss ( $r=-0.81$ ) as well as suppression of *L. rigidum* ( $r=-0.91$ ) indicate that traits contributing to early ground cover would be important for developing weed competitive wheat genotypes [57]. In another study, wheat cultivars with early canopy cover and greater biomass were found to shade grass weeds [58]. Similarly, rice cultivars having high seedling vigor suppressed weeds to a greater extent, especially in rainfed



and upland environments, where dry seeding is practiced [59]. In an earlier study, shoot length of rice was reported to have a positive correlation with fresh and dry biomass of seedlings, and vigor index [60]. Therefore, seedling vigor could play a critical role in dry-seeded rice as it helps in better crop emergence and offers greater crop competition with weeds [49]. In general, the traits associated with weed competitiveness in rice are early canopy cover, high tiller density, droopy leaves, high biomass at the early stage, high leaf area index and high specific leaf area during vegetative growth, and early vigor. In herbicide-dominant systems, using weed-competitive cultivars to suppress weeds may substantially reduce herbicide use, selection pressure for herbicide resistance, and labor costs. Most efforts to select for improved weed competitive ability have focused on aboveground traits and little is known about the importance of root competition, especially in low-input production systems. Fofana and Rauber undertook one of the few competition studies in which crop varietal differences in root growth was investigated in rice (*O. sativa* and *O. glaberrima*) [61]. They concluded that rice varieties with greater root lengths were able to cause larger suppression of weed biomass. Therefore, there is a need to quantify variation in root growth in research aimed at improving weed competitive ability of field crops.

Allelopathic crop cultivars can also be used to suppress weed seedling emergence, as they release chemical compounds through living and intact roots, and these compounds affect the growth of other plant species [49, 62]. Some progress has been made in determining the role of allelopathy in rice. Field experiments by Olofsdotter et al. revealed allelopathy accounted for 34% of overall competitive ability in rice [63]. They have argued that optimizing allelopathy in combination with breeding for other weed competitive traits (e.g., early vigor) could result in crop cultivars with superior weed-suppressive ability. However, the benefits of allelopathy for weed management in field crops, including rice, still remain largely conjectural at this stage and much research work needs to occur before these benefits can be realized by farmers.

In crops, such as rice, flooding is used to suppress weeds as most weed species cannot germinate and emerge under flooded conditions [4]. In the USA, rice is seeded in standing water (water seeding), mainly to suppress weeds. In Asia, however, flooding can be introduced only after the rice seedlings have emerged as rice cultivars capable of germinating under anaerobic conditions are not widely available. Work on such cultivars is in progress at the International Rice Research Institute (IRRI) and such cultivars will be available to farmers in the near future. Rice cultivars having tolerance of anaerobic conditions during germination are increasingly required because of the shift of rice establishment methods in many areas from transplanting to direct seeding [49]. Direct-seeded rice fields can be easily submerged immediately after crop sowing if such cultivars are available and this could provide economical and environmentally friendly weed control. However, the feasibility of such systems needs to be examined in water-limited environments.

## ***Role of Crop Density and Row Spacing in Suppressing Weed Emergence and Growth in Crops***

The impact of weeds on crops can be reduced by agronomic manipulations, such as increased crop density and reduced row spacing. Increasing crop competitiveness through the use of high crop density is a possible technique for weed management, especially in low-input and organic production systems or when herbicide resistance develops in weeds. At low crop density, crop cover early in the growing season is usually low and a large amount of resources are available for the weeds [64]. These conditions enable weeds to establish and grow quickly.

In an earlier study in wheat, doubling the crop density of several cultivars from 100 to 200 plants  $\text{m}^{-2}$  halved *L. rigidum* biomass from 100 to 50  $\text{g m}^{-2}$  [10]. In another study, increasing wheat density from 75 to 200 plants  $\text{m}^{-2}$  reduced the biomass of *L. rigidum* and increased wheat grain yield [65]. *L. rigidum* biomass declined by 43% when the wheat-seeding rate doubled from 55 to 110  $\text{kg ha}^{-1}$  [51]. In a later study, increasing wheat density from 50 to 200 plants  $\text{m}^{-2}$  in the presence of 200 plants  $\text{m}^{-2}$  of *Avena* spp. almost doubled the gross margin [66].

In Asia, rice is generally grown after transplanting of seedlings into puddled soil. Weeds are not a big problem in these establishment systems. However, there is a trend toward direct seeding (wet and dry seeding). In these systems, weeds are the number-one biological constraint. Recently, several studies reported the effect of increased seeding rates on weed suppression in direct-seeded rice systems. In one study, reducing the seeding rate from 80 to 26  $\text{kg ha}^{-1}$  increased weed biomass significantly and therefore a seeding rate of 80  $\text{kg ha}^{-1}$  was needed to avoid a large yield loss because of weeds [55]. Results from another study in India and the Philippines showed that the maximum grain yield of an inbred cultivar was achieved at 95–125  $\text{kg seed ha}^{-1}$  when grown in the presence of weeds; however, seeding rates from 15 to 125  $\text{kg ha}^{-1}$  had little effect on yield in weed-free conditions [67]. In the same study, increasing the rice seeding rate from 25 to 100  $\text{kg ha}^{-1}$  reduced weed biomass by 47–59%.

No-till farmers in many countries have widened crop row spacing to enable their seeders to cope with the large amounts of crop residues present in the field. However, wider row spacing provides more interrow space for weeds to establish and proliferate. In many crops, it is well known that reduced row spacing suppresses weed emergence and growth. Narrow row spacing improves crop competitiveness by developing faster canopy closure and allowing less light penetration to the ground. In wheat, it was shown that reducing crop row spacing from 23 to 7.5 cm decreased the seed production of *Bromus secalinus* L. [68]. Another study suggested the possibility of using narrow row spacing in corn to minimize the addition of weed seeds to the soil seed bank and to progressively deplete weed seeds in the long term [69]. In direct-seeded rice, 15–45-cm row spacing had little effect on rice grain yield in weed-free conditions; however, in weedy conditions, the widest spacing resulted in lower grain yield [70]. The critical periods for weed control can also be shorter for a crop grown in narrow rows than in wider rows. For example, the critical periods

to achieve 95% of maximum yield for weed control in dry-seeded rice were fewer in 15-cm rows (18–52 days) than in 30-cm rows (15–58 days) [71]. In another similar study at IRRI, the seedlings of *Echinochloa colona* and *Echinochloa crus-galli* emerging up to 2 months after crop emergence in dry-seeded rice produced less shoot biomass and fewer seeds in 20-cm rows than in 30-cm rows [72].

## Conclusion

In summary, weeds are the major constraint to crop production systems. Various ecologically based weed management strategies, such as the adoption of practices that enhance seed predation and seed decay, the use of a stale seedbed technique and appropriate tillage systems, retention of crop residue on the soil surface, and the use of crop cultivars with weed competitiveness and allelopathy, high crop density, and narrow row spacing, need to be integrated to achieve effective and sustainable weed control.

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# Chapter 2

## Ecology and Management of Weeds in a Changing Climate

David R. Clements, Antonio DiTommaso and Terho Hyvönen

### Introduction

The annual economic cost of weeds throughout the world is estimated at US\$ 400 billion [1]. In the USA alone, the cost of invasive plants was estimated to be US\$ 34.7 billion per year [2]. Oerke estimated that 34% of potential crop losses throughout the globe are due to weeds, as compared to 16% for pathogens and 18% for animal pests [3]. Traditionally, the cost of weed management has been principally accounted for within the agricultural sector, but in the last decade weeds, or more inclusively invasive plants, have been increasingly recognized for their negative impact on a broad array of human enterprises in addition to agriculture, including forestry, transportation, human health, recreation, and tourism [2, 4]. These collective economic influences are difficult to estimate reliably, but the estimates that have been done indicate that these are threats to be taken seriously. In the UK, for example, more than 175 million euros is used annually to control *Fallopia japonica* (Houtt.) Ronse Decr. (Japanese knotweed; Fig. 2.1) [4]. Taken together, these impacts on the economy are issues that require urgent action, particularly because weeds are a dynamic threat—they evolve in response to management practices [5, 6].

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**Fig. 2.1** Illustrations of invasive plants. **(a)** *Heracleum mantegazzianum* Sommier and Levier (giant hogweed) with author David Clements. **(b)** *Fallopia japonica* (Houtt.) Ronse Decr. (Japanese knotweed). **(c)** *Impatiens glandulifera* Royle (Himalayan balsam). **(d)** *Ambrosia artemisiifolia* L. (common ragweed) infesting corn (*Zea mays* L.). **(e)** *Sorghum halepense* (L.) Pers. (Johnsongrass). **(f)** *Lantana camara* L. (lantana). (Photo credits: **(a)** Vincent Clements; **(b, d, e)** Antonio DiTommaso; **(c, f)** David Clements)



The history of weeds and how they became weeds is tightly interwoven with that of our cropping practices [5, 7, 8], or for that matter, our horticultural, forestry, and numerous other practices that have inadvertently fostered weeds to flourish [9–11]. Thus, even aside from the specter of climate change, our response to threats caused by weeds must be as proactive as possible. Our environmental history is rife with narratives of plant invasions and weed infestations that have worsened because the actions taken were insufficient or too late [12]. Presently, we find ourselves in the midst of an increasingly worldwide dilemma in which numerous weed species are developing resistance to the nonselective herbicide glyphosate that had been considered to be a “silver bullet” for managing a vast array of weeds, including difficult-to-control perennial weed species. However, because policies governing its use were too lenient and its economic benefits within glyphosate-tolerant cropping systems were so lucrative, the selection pressure for the development of glyphosate resistance is unprecedented and creating “super weeds” [13, 14]. Until now, populations from 24 different weed species have developed resistance to glyphosate, including *Amaranthus palmeri* S. Watson (palmer amaranth), *Amaranthus tuberculatus* (Moq.) Sauer var. *rudis* (Sauer; waterhemp), *Conyza canadensis* (L.) Cronquist (horseweed), *Lolium multiflorum* Lam. (Italian ryegrass), and *Lolium rigidum* Gaudin (rigid ryegrass) [15].

The dynamic nature of weeds frequently involves expansion of their distributions [5, 16, 17]. With the increasing attention to climate change in the past several decades and impacts on biota, researchers and managers have attempted to map how the distribution of weeds might change or is already changing with climate warming and other climatic changes anticipated in temperate regions [18–22]. With these weed distribution changes, there is the prospect of increased economic damage due to weeds, either in newly infested areas or through more favorable conditions in their current ranges [23]. At the same time, historically problematic species may become less damaging in certain regions with climate change [23] but, obviously, much study is needed to ascertain which scenarios are most likely to occur. Failure to adequately predict potential impacts of weed distribution changes on agriculture, forestry, and conservation lands could have serious consequences for human sustainability. As mentioned earlier, the costs of weed management are already extremely high. Furthermore, it has been shown repeatedly that the best course of action in dealing with invasive species is “early detection and rapid response” [12]. Thus, taking proactive steps based on information on the potential spread of invasive weeds in an era of climate change should be a high priority.

In this chapter, we review current knowledge of climate change and its effects on weeds, examining regional patterns of recent range expansions across the globe, the influence of climate change on cropping systems, and biological and evolutionary responses of weeds to climate change, including resultant research and management priorities.

## Regional Patterns of Recent Weed Range Expansions

The developed world has historically been centered in Europe and North America, and, by extension, these regions have featured the most intensive weed management efforts, including the monitoring of potential expansion of weed distributions

[5, 21, 24–27]. Parts of Oceania, particularly Australia and New Zealand, have also received considerable attention in this regard [28, 29]. Economic development and weeds have also tended to go hand in hand, as illustrated by the widespread introductions of Eurasian weeds to North America [30]. Interestingly, with recent large-scale economic development in other regions, such as Southeast Asia, these regions have also experienced drastic increases in weed species introductions as a result of expanded commerce and trade [31, 32]. As accurately predicted in 1958 by Elton, in his seminal book on invasion biology, the alarming tendency arising from increased globalization is towards homogenization of the world's flora and fauna [33]. In the following section, we characterize recent weed range expansions on a regional basis, including the potential influences of climate change and other factors on these distributional shifts.

## ***North America***

As noted previously, the weed flora of North America is largely a product of its colonial history with European settlement and the ever-expanding cultivation of land, particularly during the nineteenth and twentieth centuries, with many weeds introduced through the seed trade [30]. There are some weeds native to North America that cause economic damage but the magnitude of their impact tends to be much lower than that for nonnative species. Weed managers and researchers have tended to focus efforts on weed species in North America established during the colonial period rather than “invasive weeds,” but careful survey work reveals that new weed problems are emerging due to novel species, either moving from other subregions of North America or as recent invaders from outside the continent [34]. The weed science community cannot afford to be complacent in treating weed problems based on the status quo, particularly if it can be shown that climate change and other drivers of regional weed distribution may increase the incidence of novel weeds and associated management problems.

As shown in Table 2.1 [21, 35–45], relatively recent northward expansion of weed ranges has been well documented for numerous weed species in North America, and doubtless, there are many more examples of this phenomenon [46]. This northward weed migration is of particular concern in areas where traditionally many weeds have been unable to establish because of severe winter conditions, such as in the northeastern USA [47] or Canada [48]. Of course, some weeds are predicted to decline in some regions as climate changes [23, 49]. Ziska and Runion demonstrated how *Cirsium arvense* (L.) Scop. or *Panicum miliaceum* L. (proso millet) is likely to decline in the southern parts of their ranges with climate warming [49]. Interestingly, some weed species exhibit increased tolerance to lower temperatures with increasing CO<sub>2</sub> availability [50, 51], so an increase in CO<sub>2</sub> levels even if unaccompanied by warming could stimulate poleward weed distribution extensions [52].

**Table 2.1** Recent expansion of ranges for selected weed species in North America

Weed species	Range expansion	Attributed mechanism(s)	References
<i>Centaurea stoebe</i> L. (spotted knapweed)	More northerly latitudes than in native Europe	Shift in the climatic niche due to lack of natural enemies, adaptation to drier/colder climates	Broennimann et al. [35]
<i>Datura stramonium</i> L. (jimsonweed)	Northward invasion of Canadian and northeastern US cropland since 1950s	Selection for heavier seeds, earlier growth	Weaver et al. [36]; Warwick [37]
<i>Echinochloa crus-galli</i> (L.) P. Beauv (barnyardgrass)	Northward invasion of Quebec from the USA in the nineteenth century	More rapid maturation at each life cycle stage	Potvin [38]
<i>Fallopia japonica</i> (Houtt.) Ronse Decr. (Japanese knotweed)	Northward range expansion in both Ontario and British Columbia, Canada	Genotypes with different temperature thresholds and potential hybridization	Bourchier and Van Hezewijk [21]
<i>Panicum miliaceum</i> L. (proso millet)	Northward invasion into Canadian cropland by early 1970s	Modified seed germination and dispersal characteristics	Bough et al. [39]; McCanny et al. [40]; McCanny and Cavers [41]
<i>Setaria faberi</i> Herrm. (giant foxtail)	Northward expansion into Canadian cropland by the 1970s	Modified life history traits	Warwick et al. [42]
<i>Setaria viridis</i> (L.) P. Beauv. (green foxtail)	Survival at Churchill, Manitoba, at nearly 60°N latitude (normal range 45–55°N)	Leaf production at low temperatures	Douglas et al. [43]; Swanton et al. [44]
<i>Sorghum halepense</i> (L.) Pers. (Johnsongrass)	Northward expansion by 5° latitude between 1926 and 1979	Northern populations annual (vs. perennial southern population)	Warwick et al. [45]

As indicated in Table 2.1, *Fallopia japonica* has recently shown rapid range expansion in both Ontario and British Columbia, Canada [21]. *Fallopia japonica* is one of the most aggressive invasive plants in Europe, having invaded large areas of the UK and other countries after its introduction from Asia [53]. Bourchier and Van Hezewijk compared the distribution of *Fallopia japonica* between 1971–2000 and 2000–2008 weather normals, and found an increase of 53% in suitable habitats for this invasive plant in Southern Ontario for the period 2000–2008, when temperatures were warmer than for the 1971–2000 period [21]. In contrast, only 35% of the habitat in Southern Ontario was suitable for *Fallopia japonica* for the 1971–2000 period. Similarly, with approximately half of the potentially suitable regions in British Columbia, encompassing 12.3% of the total territory invaded

by *Fallopia japonica*, there is much more potential for future expansion. Costs of *Fallopia japonica* control in both Europe and North America are considerable (e.g., between £ 1 and 8 m<sup>-2</sup> in the UK), and thus climate change scenarios threaten to increase these costs [21]. There are also indications that *Fallopia japonica* could develop increased frost tolerance [54] and genetic diversity through hybridization with *Fallopia sachalinense* (F. Schmidt) Ronse Decraene (giant knotweed), as has been documented in Washington State [55] and British Columbia [56].

It is likely that the actual range expansions already observed in North America (examples in Table 2.1 and additional examples) are just harbingers of a much larger-scale expansion of weed distributions in response to climate change and other factors, given the high dispersal characteristics of many of these weeds and their ability to respond to climate change. By simply examining eight species with the potential for range expansion (Table 2.2) [23, 57–64], it is evident that there are many ways a species can achieve this expansion.

*Pueraria lobata* (Willdenow) Ohwi (kudzu) is one of the world's worst invasive plants [65], largely known for spreading through large areas of the southeastern USA [62]. It is restricted to fairly warm environments. Sasek and Strain noted that its range is limited by low winter temperatures of  $-15^{\circ}\text{C}$  [61]. Thus, its potential northward advance in response to warming temperatures, as predicted by Sasek and Strain [61], is of great concern. In 2009, a patch of *Pueraria lobata* was found growing near Leamington, Ontario, the first verified occurrence in Canada [66]. Leamington has one of the warmest climates in Canada, but winter temperatures occasionally fall below  $-15^{\circ}\text{C}$ , such as in 1937, when a record low of  $-32^{\circ}\text{C}$  was recorded.

Another well-documented invasive plant that threatens to expand its range and impact in North America is *Sorghum halepense* (L.) Pers. (Johnsongrass) (Fig. 2.1; Table 2.2). *Sorghum halepense* is a perennial C<sub>4</sub> grass native to Eurasia that was initially adapted to the warm, humid conditions of Mediterranean Europe and Africa, and originally introduced to North America as a forage crop in the southern USA [67]. Increasingly broad climatic tolerance among new ecotypes found in North America includes increasing cold tolerance in rhizomes [45]. Furthermore, although southern populations in North America are perennial, northern populations generally have an annual life history [45]. Utilizing a damage niche model to project the potential change in the distribution of *Sorghum halepense* under a “business as usual” greenhouse gas emissions scenario, McDonald et al. predicted that the damage niche in maize could move 200–650 km northward by 2100 [23]. This would result in a much greater impact on US maize-growing regions (e.g., Midwestern USA) for this weed, which has historically had greater impacts in the southern USA [23]. In addition to this predicted increased negative impact on maize production, *Sorghum halepense* is also an increasing threat to native tallgrass prairie ecosystems under climate change [68]. When *Sorghum halepense* invades native tallgrass prairies, its rhizomatous growth allows it to advance at rates of 0.45 m year<sup>-1</sup> in addition to the deleterious effects of its allelopathic leachates on native vegetation [68].

**Table 2.2** Potential range expansion for selected weed species in North America due to climate change and adaptive traits possessed by these particular weed species

Weed species	Potential range expansion	Critical adaptive weed traits	References
<i>Abutilon theophrasti</i> Medik. (velvetleaf)	Damage niche could move 200–650 km northward in North America	Coadaptation with crops (especially maize)	McDonald et al. [23]
<i>Bromus tectorum</i> L. (cheatgrass)	Greater expansion of populations within Canada	De novo creation of weedy genotypes among ecotypes already present	Valliant et al. [57]
<i>Buddleja davidii</i> Franch. (ornamental butterfly bush)	Capable of northward movement in North America	Lack of local adaptation; current range well within climatic requirements	Ebeling et al. [58]
<i>Impatiens glandulifera</i> Royle (Himalayan balsam)	Potential for northward range expansion in North America	Differences in flowering phenology among populations	Kollmann and Bañuelos [59]; Clements et al. [60]
<i>Pueraria lobata</i> (Willdenow) Ohwi (kudzu)	Capable of expanding northward to the $-15^{\circ}\text{C}$ (low winter temperature) isocline	Rapid growth rate and ability to establish extensive systems of vines and respond to $\text{CO}_2$ enrichment	Sasek and Strain [61]; Lindgren et al. [62]
<i>Phalaris arundinacea</i> L. (reed canarygrass)	Capable of more rapid evolution at edges of range in response to climate change	Greater genetic variation and greater biomass of introduced populations	Laverigne and Molofsky [63]
<i>Sorghum halepense</i> (L.) Pers. (johnsongrass)	Damage niche could move 200–600 km northward in North America	Coadaptation with crops (especially maize)	McDonald et al. [23]
<i>Tamarix ramosissima</i> Ledeb. (saltcedar)	North of Montana in North America	Increased investment in seedling root growth	Sexton et al. [64]

## Europe

Europe has a long history of nonnative species introductions, and is reported to have as many as 2843 plant species of non-European origin [69]. Most of these species possess narrow ranges and do not cause notable management problems. However, the most alarming examples of rapid range expansion of plant species in Europe are exemplified by nonnatives (Table 2.3) [59, 70–72], suggesting that their potential range has not yet been attained. Unlike for North America, documented examples of weed range expansions due especially to climate change are limited for Europe, although range expansion limited by temperature is evident for many species. A study across altitudinal gradients in Italy found that life-form was strongly linked to

**Table 2.3** Recent expansion of ranges for selected nonnative weed species in Europe

Weed species	Range expansion	Attributed mechanism(s)	References
<i>Ailanthus altissima</i> (P. Mill) Swingle (tree of heaven)	Range expansion in southern and central Europe	Effective wind dispersal	DAISIE [70]
<i>Ambrosia artemisiifolia</i> L. (common ragweed)	Range expansion in central Europe	Niche expansion from ruderal to agricultural habitats	DAISIE [70]; Essl et al. [71]
<i>Fallopia japonica</i> (Houtt.) Ronse Decr. (Japanese knotweed)	Range expansion in central Europe	Hybridization	Hollingsworth and Bailey [72]; DAISIE [70]
<i>Heracleum mantegazzianum</i> Sommier and Levier (giant hogweed)	In northern and central Europe	Niche expansion	DAISIE [70]
<i>Impatiens glandulifera</i> Royle (Himalayan balsam)	Range expansion throughout Europe	Differences in flowering phenology among populations	Kollmann and Bañuelos [59]; DAISIE [70]
<i>Robinia pseudoacacia</i> L. (black locust)	Range expansion throughout Europe	Nitrogen fixation	DAISIE [70]
<i>Rosa rugosa</i> Thunb. ex Murray (rugosa rose)	Range expansion throughout Europe	Effective dispersal by floating seeds	DAISIE [70]

temperature for native species but not alien species [73]. The implication was that alien plants in Europe are less limited by temperature and depend more on anthropogenic factors for their spread, which does not preclude the influence of climate change but does highlight other important factors, such as land use.

Among the most troublesome nonnative species in Europe, *Heracleum mantegazzianum* Sommier and Levier (giant hogweed) and *Impatiens glandulifera* Royle (Himalayan balsam) have been successful invaders in most of northern Europe (Fig. 2.1) [17, 59], suggesting that climate is not limiting their northern distributional limit [53]. Adaptation to northern climate conditions has resulted in northern populations of *I. glandulifera* flowering earlier and producing less biomass compared with southern populations [59]. In Finland, both of these species are continuously expanding their ranges and are considered to be the most important nonnative species that should be targeted for control [74].

The distribution of two other notable nonnatives—*Fallopia japonica* and *Ambrosia artemisiifolia* L. (common ragweed; Fig. 2.1)—is evidently limited by temperature [26, 53] in Europe. The core of their ranges is situated in central Europe [70], and even though they are regularly found further north (*Ambrosia artemisiifolia* as a contaminant of sunflower [*Helianthus annuus* L.] seeds used as bird feed and *Fallopia japonica* as an ornamental), they are currently not able to establish permanent populations there. Rapid range expansion of *Ambrosia artemisiifolia* has been reported from France [75], Austria [71], and Hungary [76], whereas *Fallopia japonica* has been especially problematic in the UK [4]. A key factor in the range expansion of *Ambrosia artemisiifolia* has been a niche shift from ruderal to agricultural habitats, whereas for *Fallopia japonica* hybridization has been the most