

## Chapter 2

# Ecology and Management of Weeds in a Changing Climate

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### 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	Lavergne 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



important (Table 2.3). Because the distribution of both of these species is limited by temperature, it can be assumed that they may take advantage of climate warming to expand their ranges northwards in the future.

In arable habitats, several weed species are regarded to have potential for range expansion in the future [25]. Many of these species are found in several cropping systems and are difficult to control, making them economically important weeds to manage [77]. In Europe, the number of arable weed species declines from south to north following a climate gradient [78], suggesting that the climate warming may result in the movement of weedy species towards northern limits of the climate zones [79]. Indeed, predictions of future changes in suitable climate conditions for weed species have provided evidence for this (Table 2.4) [27]. For example, *Amaranthus retroflexus* L. (redroot pigweed) has been predicted to successfully establish about 500 km further north in the future than under current climate conditions. It is also notable that for several weed species, including *Chenopodium rubrum* L. (red goosefoot), *Papaver argemone* L. (long prickly head poppy), and *Sinapis arvensis* L. (wild mustard), a 60% decline in suitable climate conditions in the future is predicted. These findings highlight species-specific responses to climate change and subsequent effects on their ranges, which should, however, be confirmed with field experiments that assess reproductive success outside the current ranges [80, 81]. Importantly, the combined effects of northward extension of crop regions and potential climate warming trends [82] will have significant consequences for weed management in Europe, as in other continents [18, 20, 27].

## *Oceania*

The position of Australia and New Zealand in the southern hemisphere makes the potential trend of southward changes in weed distribution of greater interest than northern regions, from the standpoint of climate change. As with North America and Europe, such distributional changes (southward) have been documented for a number of weed species (Table 2.5) [22, 28, 29, 83, 84].

Gallagher et al. showed how 11 species of alien perennial grasses that were either shortlisted or listed as weed threats of national importance in Australia could undergo alterations in distribution with climate change [29]. As is seen worldwide, these grasses can have devastating impacts on crops and rangeland in Australia, even though most of these were deliberately introduced as forage grasses. However, because these grasses are already near the edge of their climate optima in Australia, if temperatures along with drought conditions increase through climate change as predicted, these grasses may not be able to maintain their current extent [29]. For example, the range of *Cortaderia selloana* (J.A. and J.H. Schultes) Aschers. and Graebn. (pampas grass) is predicted to decline by 68% by 2050, according to a climate change scenario for Australia generated from four models. Likewise, the other grass species listed in Table 2.5 that have hitherto featured rapidly expanding ranges are predicted by Gallagher et al. [29] to decline by 2050: *Eragrostis curvula* (Schräd.) Nees (African lovegrass), *Nassella aneesiana* (Trin. and Rupr.) Barkworth

**Table 2.4** Potential range expansion from 2051 to 2080 for selected weed species in Europe due to climate change under two scenarios developed from climate land-use (CLU) models. (From Hyvönen et al. [27])

Species	Distribution	Percent change with less severe scenario	Percent change with more severe scenario
<i>Amaranthus graecizans</i> L. (Mediterranean amaranth)	Southern	19.3	25.9
<i>Amaranthus retroflexus</i> L. (redroot pigweed)	Southern and central	26.2	44.6
<i>Cardaria draba</i> (L.) Desv.	Southern and central	15.3	21.6
<i>Chenopodium vulvaria</i> L. (stinking goosefoot)	Southern and central	20.1	26.1
<i>Consolida regalis</i> Gray (royal knight's-spur)	Central	5.7	11.7
<i>Coronopus squamatus</i> (Forssk.) Asch. (greater swinecress)	Southern and central	13.8	14.5
<i>Fumaria parviflora</i> Lam. (fineleaf fumitory)	Southern and western	26.3	39.6
<i>Fumaria vaillantii</i> Loisel (earth smoke)	Central	3.6	0.4
<i>Neslia paniculata</i> (L.) Desv. (ball mustard)	Southern, central, and eastern	10.8	17.6
<i>Papaver hybridum</i> L. (round prickly head poppy)	Southern and western	26.5	41.1
<i>Papaver rhoeas</i> L. (common poppy)	Throughout Europe	18.3	22.8
<i>Portulaca oleracea</i> var. <i>oleracea</i> L. (common purslane)	Southern and central	23.2	30.9
<i>Ranunculus arvensis</i> L. (corn buttercup)	Southern and central	21.3	31.3

(Chilean needle grass), *Nassella trichotoma* (Nees) Hack. (serrated tussock), *Sporobolus africanus* (Poir.) Robyns and Tourn. (Parramatta grass), *Sporobolus pyramidalis* Beauv. (giant rat's tail grass), and *Themeda quadrivalvis* (L.) Kuntze (grader grass). Interestingly, *Eragrostis curvula* and *Themeda quadrivalvis* are also found in areas in Australia where their global niches do not predict them, whereas the other species have not yet fully expanded to occupy all areas in Australia where the climate is suitable [29]. These findings suggest that some grasses could defy range predictions based on global climate niche modeling. Certainly, in the case of *Nassella* spp. (needle grass species), there is a high likelihood that their current high levels of infestation in southeast Australia will be reduced by anticipated warming trends in the region [29]. The case of *Nassella* spp. is further complicated by the fact that these grasses still have suitable areas that are yet to be colonized based on their potential climate niches; hence, there are still many parts of Australia that are vulnerable to new invasions by *Nassella* spp.

**Table 2.5** Recent expansion of ranges for selected weed species in Oceania

Weed species	Range expansion	Attributed mechanism(s)	References
<i>Aira cupaniana</i> Guss. (silvery hairgrass)	Expansion into more arid parts of New South Wales	Decreased plant height	Buswell et al. [83]
<i>Cortaderia selloana</i> (J.A. and J.H. Schultes) Aschers. and Graebn. (pampas grass)	Spread widely throughout southern Australia since 1901	Wind dispersal, superior competitor	Gallagher et al. [29]
<i>Eragrostis curvula</i> (Schröd.) Nees (African lovegrass)	Spread widely throughout southern, eastern, and western Australia since 1914	Superior competitor, low palatability to grazers; drought tolerant	Gallagher et al. [29]
<i>Facelis retusa</i> (Lam.) Sch. Bip. (trampweed)	Expansion into more arid parts of New South Wales	Decreased plant height	Buswell et al. [83]
<i>Hyparrhenia hirta</i> (L.) Stapf. (Coolatai grass)	Rapid spread to all Australian states from New South Wales since the 1890s	High population growth in areas with 175–600 mm of rain; ability to germinate in a broad range of temperatures and moisture levels	Chejara et al. [84]
<i>Nassella neesiana</i> (Trin. and Rupr.) Barkworth (Chilean needle grass)	Rapid spread in southeastern Australia since 1941	Transport in sheep wool, mowing equipment, and by natural means (wind, water)	Gardener et al. [28]; Bourdöt et al. [22]; Gallagher et al. [29]
<i>Nassella trichotoma</i> (Nees) Hack. (serrated tussock)	Rapid spread in southeastern Australia since 1937	A variety of seed dispersal mechanisms: wind, animals, and contaminated feed	Gallagher et al. [29]
<i>Polycarpon tetraphyllum</i> (L.) L. (fourleaf allseed)	Expansion into more arid parts of New South Wales	Decreased plant height	Buswell et al. [83]
<i>Silene gallica</i> L. (French catchfly)	Expansion into more arid parts of New South Wales	Decreased plant height	Buswell et al. [83]
<i>Sporobolus africanus</i> (Poir.) Robyns and Tourn. (Parramatta grass)	Spread widely throughout Australia since 1802	Seed dispersal via wind, water, and machinery	Gallagher et al. [29]
<i>Sporobolus pyramidalis</i> Beauv. (giant rat's tail grass)	Spread rapidly across northern and eastern Australia since 1921	Seeds carried on animal fur	Gallagher et al. [29]
<i>Themeda quadrivalvis</i> (L.) Kuntze (grader grass)	Spread rapidly across northern and eastern Australia since 1935	Seed dispersal via wind, water, and machinery	Gallagher et al. [29]
<i>Trifolium glomeratum</i> L. (cluster clover)	Expansion into more arid parts of New South Wales	Decreased plant height	Buswell et al. [83]

As with weeds throughout the world [6, 48], questions remain as to how stable the fundamental niches of invasive weeds are and as assumed by the modeling performed by Gallagher et al. [29]. Buswell et al. studied a variety of invasive species to determine whether their morphology had changed under environmental conditions experienced since their introduction to Australia [83]. Seventy percent of the species examined using historical herbarium records showed changes in at least one trait, with the most commonly observed modification being a change in height. Changes in height were found in 8 of the 21 species, including *Facelis retusa* (Lam.) Sch. Bip. (trampweed), *Polycarpon tetraphyllum* (L.) L. (four leaf all-seed), *Silene gallica* L. (French catchfly), and *Trifolium glomeratum* L. (cluster clover; Table 2.5), species now inhabiting the arid western portion of New South Wales. The relatively large number of cases where height decreased is consistent with the view that these species underwent selection for decreased height to cope with the more arid conditions, and the implication is that this kind of selection could enable invasive plants like these to thrive and spread under climate change. Buswell et al. did not eliminate the possibility that much of the observed height differences might be due to phenotypic plasticity, but through tracking the trend in the same location through time, there were strong indications that genetic differences were represented in the results [83].

As with North America and Europe, there is a considerable amount of research being done to predict further spread of invasive species. For example, *Senna obtusifolia* L. (sicklepod) is currently found in northern Australia but could move into southern regions, as ecotypes have been identified that are adapted to a range of temperatures [85].

## Asia

For Asia, the north–south axis does not carry the same significance in terms of climate change and floral distribution as seen in North America, Europe, and Oceania. However, recent modeling work by Qin et al. suggests dramatic impacts of predicted climate change on the distribution of two highly invasive alien annual herbs, *Ambrosia artemisiifolia* and *Ambrosia trifida* L. (giant ragweed), in China [86]. The projected distribution under future climatic change scenarios suggests an overall increase in *Ambrosia artemisiifolia* distribution with further expansion to climatically favorable locations in southeastern China and northern Taiwan. The models reveal a significant progressive northward and northeastward contraction in *Ambrosia trifida*'s range in China, with southeastern Tibet and northern Taiwan as novel and potentially suitable climate habitats.

Japan experiences a substantial range in climate along its north–south axis and its overall climate has changed in the past few decades as indicated by earlier flowering of *Ginkgo biloba* L. trees in the spring [87]. Tsutsumi modeled the potential range expansion of *Senecio madagascariensis* Poir. (fireweed) in Japan using a maximum entropy ecological niche modeling approach (Maxent) [88]. Tsutsumi

predicted that the northern extent of *Senecio madagascariensis* could shift from where it is currently at 36.9°N in southern Tohoku to 39.1°N in central Tohoku, with temperature in the warmest quarter of the year identified as the key variable predicting its range [88]. Thus, if temperatures continue to rise, invasive plants like *Senecio madagascariensis* that require higher temperatures to complete their life cycle would be predicted to move northward on the Japanese archipelago.

## *Africa and South America*

As with Oceania, the southward expansion of weed distributions is important to monitor in Africa and South America under climate change. *Lantana camara* L. (lantana) is a troublesome invasive species native to South America, now thriving in many subtropical habitats throughout the world (Fig. 2.1). It was first collected by Dutch explorers in the 1640s, who introduced it to European gardens where hybrids were produced and distributed throughout the globe [89–91]. In Kenya, *Lantana camara* has spread over large areas, threatening wildlife habitat [92]. It has likewise spread rapidly in other African countries. For example, the area infested by *Lantana camara* increased by roughly sixtyfold in South Africa between 1962 and 2000 [90, 93, 94]. As in other parts of the world, *Lantana camara* affects South African ecosystems in many deleterious ways, including impacts on water availability and biodiversity [94]. Vardien et al. utilized correlative bioclimatic models to demonstrate that *Lantana camara* threatens to expand its South African range even further within a few decades [94]. A climate scenario for the year 2050 predicted increased habitat suitability in areas where *Lantana camara* was already present and in a few additional areas as well, thus forecasting greater impacts of the plant on South African ecosystems unless it is effectively managed. Taylor and Kumar modeled potential changes in climate suitability for *Lantana camara* in Queensland, Australia, and found that although further potential invasion was predicted for 2030, for future climate projected to 2070 and 2100, a dramatic decline in available niche space in Queensland was forecasted [95]. Once temperatures increase beyond a specific threshold and combine with reduced rainfall, this subtropical plant has physiological challenges [96]. These predictions from northeastern Australia are likely to apply to more equatorial regions of Africa and other areas near the equator around the globe as well.

*Lygodium microphyllum* (Cav.) R. Br. (the Old World climbing fern), native to the Old World wet tropics and subtropics of Africa, Asia, Australia, and Oceania [97], has been recently causing serious problems in a variety of habitats in the New World, in particular, Florida where it overtops trees and smothers plant communities with its extensive growth [98]. Goolsby modeled its potential spread in the New World and found that much of Florida as far north as Tampa was vulnerable to further invasion, based on current climatic conditions [99]. Furthermore, Goolsby's model [99] suggested that large areas within Central America, the Caribbean, and South America could be colonized by *Lygodium microphyllum* in addition to Jamaica and



Guyana, which have already been colonized [97]. Aggressive Old World subtropical weeds, such as *Lygodium microphyllum*, are likely to benefit from changing climates in terms of spread through the New World subtropics, but little information is available on South American weed invasions.

## **Influence of Climate Change on Weed Competition in Cropping Systems**

There have been various predictions made about the impact of climate change on the world's crops; some predictions have indicated an increase in crop yields by as much as 13 % by 2050 due to increased CO<sub>2</sub> production [100], but other factors such as increased drought severity, increased temperature during the growing cycle, and changes in monsoon patterns may result in lower yield gains or worse [101, 102]. For example, the Fourth Assessment Report of the World Meteorological Organization/The United Nations Environment Programme (WMO/UNEP) Intergovernmental Panel on Climate Change (IPCC) released in 2007 predicted that decreases in moisture availability will accompany rising temperatures in semiarid regions of Asia, Africa, and Latin America and will become even more severe during the twenty-first century [103]. Longer growing seasons in temperate regions could provide wider windows of opportunity for infestations of weeds and other pests [104]. Weeds figure prominently in the uncertainty surrounding the impact of climate change on cropping systems, because of differential impacts of changing moisture regimes, temperatures, and CO<sub>2</sub> levels on weeds versus crops [101]. In general, weeds have an advantage in making use of increased CO<sub>2</sub> levels [101, 105] with some possible exceptions [106], indicating that without adequate weed management, climate change could lead to increased yield losses due to weeds. Furthermore, many weed species may grow better than crops under warmer conditions. In the USA, many of the invasive plants infesting warm season crops originated in tropical or warm temperate regions, and warming would foster even greater northward movement of such crops [46]. If the crops themselves can be grown further north under climate change, the weeds are likely to move with them, as has frequently been observed in the past when a crop is grown outside its normal range [5].

It is clear that prediction of changes in weed distribution often requires tracking potential changes in the distribution of the cropping systems with which the weeds have coevolved [5]. As Marini et al. point out, disentangling the relationship between alien and native plant communities is challenging because human settlement and economic activity is related to climate [73, 107]. Types and relative intensity of management dictate weed distribution at local and regional scales [34]. For example, intensification of cereal production practices dramatically altered weed community composition in Spain between 1976 and 2007 [108]. Geographic shifts in the areas where particular crops are grown have been predicted based on projected changes in climate [103, 109]. Another management response already being carefully considered and implemented is strategically changing the varieties and/or types of crops being grown within certain regions in anticipation of climate change [100, 109, 110].

## Biological and Evolutionary Responses of Weeds to Climate Change

Actual and predicted ecophysiological changes in weed species in response to climate change are complex, due to the range of impacts that climate change has on plant biology. Four important components to consider are: responses to increased CO<sub>2</sub> levels; responses to increased temperatures predicted in temperate regions; responses to increased climate variability such as changes in moisture availability; and, finally, actual and predicted evolutionary adaptation by weeds under climate change. These four components are examined in detail as follows.

### *Responses to Increased CO<sub>2</sub> Levels*

Plants in general are expected to exhibit an increased growth rate in response to enhanced CO<sub>2</sub> levels due to the obvious impact of increased carbon available for fixation via photosynthesis, when increased CO<sub>2</sub> level is considered independent of other climatic factors. As mentioned previously, weed species often exhibit differential responses to CO<sub>2</sub> levels compared with crop species. Ziska examined the responses of six invasive species to past, present, and projected future CO<sub>2</sub> levels (284, 380, and 719  $\mu\text{mol mol}^{-1}$ , respectively) and observed an average increase in plant biomass of 46% among the species tested, with the greatest response of 72% by *Cirsium arvense* L. (Canada thistle) [111]. The growth response from past to present was significantly higher at 110%, with *Cirsium arvense* once again exhibiting the greatest response (180%). The remaining species *Convolvulus arvensis* L. (field bindweed), *Euphorbia esula* L. (leafy spurge), *Sonchus arvensis* L. (perennial sowthistle), *Centaurea stoebe* L. (spotted knapweed), and *Centaurea solstitialis* L. (yellow star thistle) also demonstrated increased biomass with CO<sub>2</sub> enrichment [111]. Given the threefold greater response of these species compared with other plant species tested, Ziska concluded that increased CO<sub>2</sub> levels could result in increased selection of these weed species over other plants, including crop plants [111]. However, it should be noted that in some cases, crop plants could produce greater biomass relative to weeds. For example, Ziska observed that when soybeans (*Glycine max* L.) were grown in competition with the well-known agronomic weed, *Abutilon theophrasti* Medik. (velvetleaf), with elevated CO<sub>2</sub> levels, competition favored the soybeans whereby soybean yield components, including pod numbers plant<sup>-1</sup>, were higher under increased CO<sub>2</sub> [106]. Similarly, when another widespread agronomic weed *Chenopodium album* L. (common lamb's-quarters) was grown in a Canadian pasture community, CO<sub>2</sub> enrichment failed to elicit increased growth in *Chenopodium album* [112]. Thus, although increased CO<sub>2</sub> levels clearly promote enhanced weed growth in general, weed-crop competition relationships should be evaluated on a case-by-case basis.

Photosynthetic pathway is a critical factor to consider, particularly since many of the world's most problematic weeds are C<sub>4</sub> plants, which tend to photosynthesize

more efficiently at higher temperatures, and therefore would likely be able to utilize increased CO<sub>2</sub> levels compared to C<sub>3</sub> plants, including crops [113]. Alberto et al. observed that the C<sub>4</sub> weed *Echinochloa glabrescens* Munro ex Hook. f. gained a photosynthetic advantage over rice (*Oryza sativa* L.) at elevated temperatures [113].

Of course, it is unrealistic to consider increased CO<sub>2</sub> in isolation of other factors, given the multiple dimensions of climate change. For example, Nonhebel found that although enhanced CO<sub>2</sub> was predicted to increase wheat (*Triticum aestivum* L.) yields in Europe, these effects would be neutralized by reduced growth due to an elevated temperature [114]. However, if drought occurred due to limited water availability under climate change, wheat yields would be depressed [114]. Similar three-way interactions should apply to other plant species, including many weed species, highlighting the value of studying the impact of multiple climatic factors on weeds and their interactions with crops or native plants.

### ***Responses to Increased Temperatures Predicted in Temperate Regions***

Examples of potential responses of weeds to increased temperatures, as well as the actual observed trends due to recent climate warming, are presented in Tables 2.1–2.5 and discussed with respect to specific global regions. Fundamentally, warmer temperatures provide plants with an opportunity to complete their life cycles within a shorter time period, and thus allow certain weeds to occupy areas where they formerly could not reproduce, or at least reproduce efficiently enough to be successful. For example, recent trends towards warmer temperatures in temperate regions have promoted earlier flowering in a variety of ecosystems and over a wide range of plant species [115, 116]. However, there are also upper temperature thresholds that impact plant growth; and thus in areas such as parts of Australia where climate change is predicted to result in very high temperatures accompanied by moisture shortage, even very prolific weed species may decline in such extreme conditions [29]. Woody plants, particularly shrubs and other weeds physiologically adapted to high temperatures and moisture stress, are expected to prevail in regions experiencing extreme impacts of rising temperatures [117]. Similarly, C<sub>4</sub> plants are generally predicted to fare better in regions experiencing warming. For example, *Rottboellia cochinchinensis* (Lour.) W.D. Clayton (itchgrass), a C<sub>4</sub> plant that currently occupies a fairly restricted range in the southern USA, is expected to expand its range and become troublesome over a much larger area of the country [118]. Established latitudinal niches for particular weed species could be dramatically altered if mean temperatures in temperate arable regions increase by just a few degrees Celsius as anticipated under even relatively conservative climate change scenarios [23]. In Europe, the distribution of C<sub>4</sub> weeds is limited to a great extent by temperature [79]. Climate warming could enable their expansion from temperate to boreal region [27].

## ***Responses to Increased Climate Variability***

Simply accounting for the impacts of rising levels of greenhouse gasses on a single parameter, such as temperature, is not sufficient to account for climate change; and in fact, it is not appropriate to refer to climate change as “global warming” because the extreme variation expected from region to region may lead to cooler temperatures in certain regions. Thus, efforts to account for an array of potential climate variables affected by global climate change are vital and such efforts have been underrepresented in the literature to date [119]. More variable precipitation, particularly, when accompanied by warmer temperatures, will likely lead to increased drought; some studies have addressed the potential impact of such conditions on plant life, with once again weeds expected to fare better than native plants or crop plants [120–122]. This projected scenario is of concern and will require improved weed management strategies in regions especially affected by this climatic variability [123].

Considerable research on how annual plant communities are adapted to variable rainfall levels in arid and semiarid ecosystems has been performed [124, 125]. This knowledge may provide some clues as to the ability of annual weeds to thrive in currently more mesic environments but predicted to experience more variable rainfall as the climate changes [126]. Robinson and Gross studied how increased variability in precipitation would impact two common annual weeds in the USA, *Chenopodium album* and *Setaria faberi* Herrm. (giant foxtail) [126]. As might be expected, the impact of periodic droughts varied, depending on plant life stage, but overall, *Chenopodium album* showed greater resilience under prolonged dry periods than *Setaria faberi*. The authors concluded that predicted changes in the occurrence and severity of precipitation events are likely to alter relative abundances of agriculturally important weeds [126].

## ***Actual and Predicted Evolutionary Adaptation by Weeds under Climate Change***

Although considerable progress has been made in predicting potential weed distributions using bioclimatic models, the accuracy of these predictions may always be compromised to some extent by the ability of weeds to adapt [6]. There are an increasing number of examples illustrating how weed species are effectively adapting to selection pressures as the climate continues to change, such as extremes of heat or moisture deprivation (Tables 2.2 and 2.5) [6, 48]. Therefore, as in all areas of weed science, there is a need for more “evolutionary thinking” [127] in assessing the risk of increased weed invasions under climate change. Weed species, in general, can be viewed as a complex set of ecotypes occurring both in their native and introduced ranges, with genetic variation and the potential for natural selection even among species exhibiting a predominantly selfing strategy [5, 127]. Climate change introduces additional selection pressures that add to the dynamic environments that

weeds must already adapt to, including adaptation to normally variable climate, heterogeneous environments, herbicide applications, and various other anthropogenic factors. Recent studies have examined actual and potential evolutionary responses to climate changes, such as the work by Buswell et al. in Australia that revealed changes in weed attributes [83], or the evolutionary adaptations of *Fallopia japonica* or *Sorghum halepense* observed in North America [21, 45, 56].

Many examples of weed evolutionary responses are related to adaptations to increased temperatures, but Franks et al. demonstrated that *Brassica rapa* L. (field mustard) exhibited an adaptive response to multiyear droughts that may come to typify modified climates in more arid areas [128]. They compared pre-drought genotypes to genotypes exposed to growing seasons shortened by drought and found first flowering was advanced by between 1.9 and 8.6 days, depending on the population. There is a need to account for such interpopulation variability in weed responses to be able to better model and respond to such evolutionary changes under the various predicted climate change scenarios [6, 127, 129].

## Use of Predictive Models to Develop Early Warning Systems

As indicated throughout this chapter, although much research has been done to gain a better understanding of the impact of climate change on weeds, there are still many gaps in our knowledge. As with climate change in general, the use of predictive models is critical and as climate change modeling is undergoing continual fine-tuning, predictive models for weed responses must be concomitantly updated. However, improved predictive modeling requires better empirical understanding of weed evolution and ecology [130]. Weed ecology is a multifaceted discipline requiring extensive knowledge specific to the individual weed species. Taken together, predictive modeling and improved understanding of weed biology and ecology should provide more effective early warning systems to track changes in weed distributions and their impact under climate change.

An increasing number of modeling approaches and techniques have been developed in recent years to predict and map the expected ranges of habitat suitability of various invasive weeds. These models have helped to assess the potential geographic distributions of these species in response to different factors, such as climate change and land-use type. Among these modeling approaches, niche-based species distribution models [131–133] have been used for assessing and identifying regions with a high invasion potential. These models use known species distributions combined with a set of environmental variables to develop a correlative model of the environmental conditions that meet a species' ecological requirements [133]. This approach makes it possible to project modeled niches into new regions and under future climate change scenarios, and ultimately to estimate the geographical distribution of suitable conditions.



One concern with distribution predictions for invasive species is the type of range information (native, invaded, or full ranges) that is used to develop the niche-based models. A comprehensive list of concerns with modeling plant species' distributions is provided in Thuiller et al. [134]. Models based on data from the native range assume that the same environmental factors determine the distribution of the species in the adventive range. However, these predictions may not adequately reflect the distribution of an invasive species in its introduced range [135]. On the other hand, "climatic niche shifts are rare among terrestrial plant invaders" giving support for the use of ecological niche models [136].

Models using data from a previously invaded range may be more appropriate and accurate because the fundamental niche is likely to be more fully realized in invaded ranges than in the native range, where the species may be constrained by such factors as competition and dispersal barriers. Combining native and alien distribution records in models (i.e., discriminative correlative models) may be most insightful [137], but has been shown not to consistently improve model projections [138]. However, given niche differences across native and introduced ranges, distribution models using introduced range data alone may be more valid in some cases [35, 139]. Despite contrasting views about the robustness of these methods, niche-based models and the presence of species in a region can provide insight into those factors that may favor or restrict the expansion of invasive species over a large scale. For example, Qin et al. used ecological niche maximum entropy (Maxent) modeling based on occurrence records of *Ambrosia artemisiifolia* and *Ambrosia trifida* in their native and introduced ranges to predict the potential distribution of these two invasive congeners in China under current climate conditions and under future climate projections [86].

The recent development of a large range of modeling tools for predicting potential weed distributions and to determine what areas are vulnerable to further weed invasion with or without climate change is very promising [140]. However, this ability to predict possible future changes in weed distribution must be accompanied by sufficient resources, to develop these tools, utilize them, and then take active measures to prevent new weed infestations.

## Conclusion

As with the other issues discussed with respect to climate change, there is an urgent need to address the threats posed by weeds under climate change, and formulate better management approaches fostered by comprehensive research efforts. One distinction between problems associated with weed management and climate change, not necessarily true for other climate change issues, is that with or without climate change, worsening of economic and ecological impacts of weeds is fairly predictable. Invasive plants will continue to spread regardless of climate change, particularly in an era of ever-increasing globalization and movement of goods [31]. As seen in this review, many plant invasions will progress farther and faster

if assisted by climate change, and climate change is likely to increase evolutionary adaptation of weeds to climate extremes. However, encouraging progress is being made in our understanding of many of these, often, complex dynamics. Prospects for tracking and mitigating anticipated impacts of weeds in a changing climate are good, provided sufficient resources continue to be made available.

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