Mini Review

Climate Change Impacts on Weed–Crop Interactions and Their Implications for Agricultural Productivity: A Review

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Abstract | Climate change is progressively altering weed activities, crop–weed interactions, and the success of weed management techniques modifying the dynamics of agroecosystems. The review links plant physiological responses to shifts in weed communities, crop–weed competition, and management at multiple scales. It highlights thresholds related to drought, heat stress, and herbicide resistance that threaten traditional weed control, emphasizing the need for climate-resilient management. This review integrates recent evidence for mechanistic links between elevated atmospheric CO_2, rising temperature and increasing variability in rainfall which have been demonstrated to increase weed pressure and crop yield losses at the level of major agricultural systems. Climate-induced physiological traits in weeds such as, elevated growth rates, phenological advancements and increased stress tolerance, are tipping competitive levels towards the weed species, particularly during the early crop establishment. These additional impacts amplify the changes caused by asynchronous emergence patterns, and more heat damage due to decreased crop resilience. In the major cereal-based systems such as wheat and rice, climate variability is affecting higher average yield losses, culminating in yield instability. Weed-induced yield reductions are increasingly pronounced in South Asia, such as Pakistan, where agriculture is highly susceptible to climatic variabilities and interactive influences of temperature stress coupled with water scarcity and delayed sowing patterns. Climate change is also indirectly affecting herbicide efficacy and speeding the evolution of herbicide resistant biotypes, complicating control measures. The review highlights the need to move from the excessive dependence on conventional weed control approaches towards sustainable, climate-resilient integrated weed management systems that use cultural, mechanical and chemical methods in an interdependent manner. Synthesized evidence from recent studies shows that weed biomass and competitive ability often increase by 15–70% under future CO_2 concentrations and warming, with crop yield declines associated with these impacts rising by 5–25%, contingent on particular crops, the functional group of weeds examined (e.g. C3 vs. C4) or different climatic conditions. Our review takes a scale-specific view, linking plant-level physiological responses to shifts in weed communities, crop–weed competition and management outcomes at field and regional scales. It also delineates new thresholds related to prolonged drought, increased heat-stress events and the evolution of herbicide resistance that put conventional weed management practices at risk of failure as climate change advances; thus underscoring the need for more intensive use of climate-resilient integrated weed management measures. Gaining a better understanding of how these interactions are changing in response to climate change drivers will be essential for maintaining crop yield in the future.

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Introduction

Climate change is a major challenge for agriculture around the world as it affects crop productivity, resource availability, agroecosystem dynamics, among other factors (Peters *et al*., 2014). Environmental changes, characterized by growing atmospheric concentrations of carbon dioxide (CO_2), rising global mean temperatures and changing precipitation patterns are affecting both crop growth as well as the dynamics of associated biotic stresses, especially weeds (Malarkodi et al., 2017). As agricultural pests, weeds are second only to a few insect pests and diseases in terms of yield loss, and in many cropping systems outnumber both insect pests and diseases combined. In addition to their high ecological plasticity and adaptive ability, they are also among the key actors shaping maximally feasible agricultural productivity potential under different scenarios of climate change (Ramesh *et al*., 2017).

Weeds, in contrast to cultivated crops that have been genetically improved for specific environments and growth conditions, tend to be either highly heterozygous, plastic or fast-cycling species (Mahajan *et al*., 2012). Such characteristics allow them to respond better to anthropogenic perturbations that include increased CO_2 and temperature changes. That is, weeds will be able to grow faster, accumulate more biomass and use water for growth with greater efficiency at elevated CO_2 levels compared to crops (Ziska and Dukes, 2011). Lastly, the differential mechanisms of C_3 and C_4 plant responses to changing climate variables can confound crop–weed interactions further by eroding competitive hierarchies within agroecosystems (Korres *et al*., 2016). Consequently, weeds are not just inert players within agricultural systems but active organisms with extraordinary ability to take advantage of a switching environmental context in real time (Amare, 2016).

One of the most visible impacts of climate change is the shift in distribution and species composition of weed flora. Changing temperature and precipitation regimes are moving the range of thermophilic and/or invasive weed species into areas that were previously unfavorable, while also altering the composition of native weed communities (Vila *et al*., 2021). These transitions take place at different ecological scales like range shifts at landscape, niche shifts at community and trait-based adaptations at species scale (Ramesh *et al*., 2017). These changes are beginning to create new assemblages of weeds that are more ecologically fit and have added layers of complexity in terms of weed management, thus greatly complicating the already difficult agricultural practice (Singh *et al*., 2011).

Besides its impact on distributions, climate change is likely to increase crop–weed competition and thus yield losses. Changes in germination timing, growth duration and resource acquisition strategies can influence the timing of critical weed interference period which translate directly to competition for light, water and nutrients (Vila *et al*., 2021). Research shows that weeds can gain a greater benefit from higher CO_2 and temperature changes than crops, resulting in: 1) competitive rankings shifting in favor of weed species and 2) even more pressure on crop productivity (Ziska and Dukes, 2011; Knezevic and Dutta, 2015). Sustained high-density weed populations over the years can alone determine yield losses, but weed competition associated with abiotic stress, such as drought and heat, in resource-poor agriculture may exacerbate the magnitude of perceived variability in grain yields (Oerke, 2006).

The impact of climate–weed interactions on weed management practices, especially herbicide efficacy, is another key dimension of climate–weed interactions. Key environmental variables (temperature, humidity and atmospheric CO_2) can have an appreciable effect on their absorption, translocation and overall effectiveness. Some evidence shows climate change could decrease herbicide activity in some situations, whereas in others, can accelerate the evolution of resistance to herbicides within weed populations (Matzrafi, 2019; Vila-Aiub *et al*., 2009). The need to manage both cases, presents a double-challenge complicating weed management strategies and highlighting the necessity of more integrated and adaptive management approaches.

Weeds also have fascinating evolutionary constraints that would allow them to quickly respond, as species, both to changes in climate and anthropogenic pressure such as those imposed by herbicides (Storkey *et al*., 2021). Climate change adds an extra level of selection pressure that enables weed genotypes with higher feedback loops of stress tolerance, growth and reproduction efficiency to dominate (Ramesh *et al*., 2017). This evolutionary capacity together with their ecological resilience give weeds the ability to track changing climates better than many crop species, thus consolidating their competitive and adaptive dominance in agroecosystems (Korres *et al*., 2016).

This multifaceted effect is indicating that climate change is not only causing weed pressure but also changing weed dynamics across ecological, physiological and management levels. An in-depth understanding of such changes is vital for a sustainable and climate-resilient management of weeds. Thus, the objective of this review is to summarize the available knowledge on climate change effects on weed distribution, biology and crop–weed interactions in a contexts related to their prompt potential impacts upon crop productivity and managing long term strategies. Weed–crop interactions from climate change occur across multiple biological and ecological levels. Physiologically, elevated CO_2, temperature, or altered moisture affect photosynthesis, growth, resource use, and stress tolerance. These responses influence community processes like weed emergence, reproduction, seed bank dynamics, and species persistence (Chaudhary *et al*., 2026). Changes in species composition and evenness affect competition within cropping systems, impacting productivity and ecosystem services. Regionally, these interactions involve species migration, invasions, and shifting agro-ecological conditions (Early *et al*., 2016).

These interconnected scales, linked by feedback loops, show that improved physiological performance under elevated CO_2 can lead to more weed fecundity and larger seedbanks, affecting short-term population growth. Changes in weed community composition may influence herbicide effectiveness and management at farm and regional levels (Guo *et al*., 2026). Therefore, studying climate change effects on weed dynamics requires an integrated framework that considers physiological plasticity and demography within population, community, and agroecosystem processes (Nawaz *et al*., 2026).

The Figure 1 given below shows a conceptual framework regarding the weed biology and crop production as impacted by climate change.

Climate change drivers influencing weed dynamics

Climate change is the result of certain interrelated environmental drivers, most notably elevated atmospheric carbon dioxide (CO_2) levels; increased temperatures and altered precipitation regimes (Kaur *et al*., 2024). These drivers are changing plant growth environments and ecological dynamics of agroecosystems. Their importance in weed science is their influence on weed emergence, biomass, competitive interactions and responses to control, such as herbicides (Upasani and Barla, 2018). Climate change, by contrast to the non-sustained and random climate variability of isolated years, also referred to as environmental noise, represents a directional change that may have effects on weed population processes with long time-horizons (Bradley *et al*., 2010; Patterson, 1995).

Climate, and by extension atmospheric CO_2 concentration, is a key driver of most physiological processes within plants. Photosynthesis relies on CO_2 as a key substrate; therefore, higher concentration could boost carbon assimilation, especially for C_3 plants. Research indicates that many weed species have strong growth responses to elevated CO_2, such as increased leaf area, biomass accumulation and reproductive output (Ziska, 2021). Also, elevated CO_2 often increases water-use efficiency as a result of downsized stomatal conductance which gives weeds a better chance to grow in water-limited conditions. The expression of these physiological advantages may not be as pronounced in crops, potentially transferring competitive interactions toward weeds in future climates (Ward *et al*., 2000).

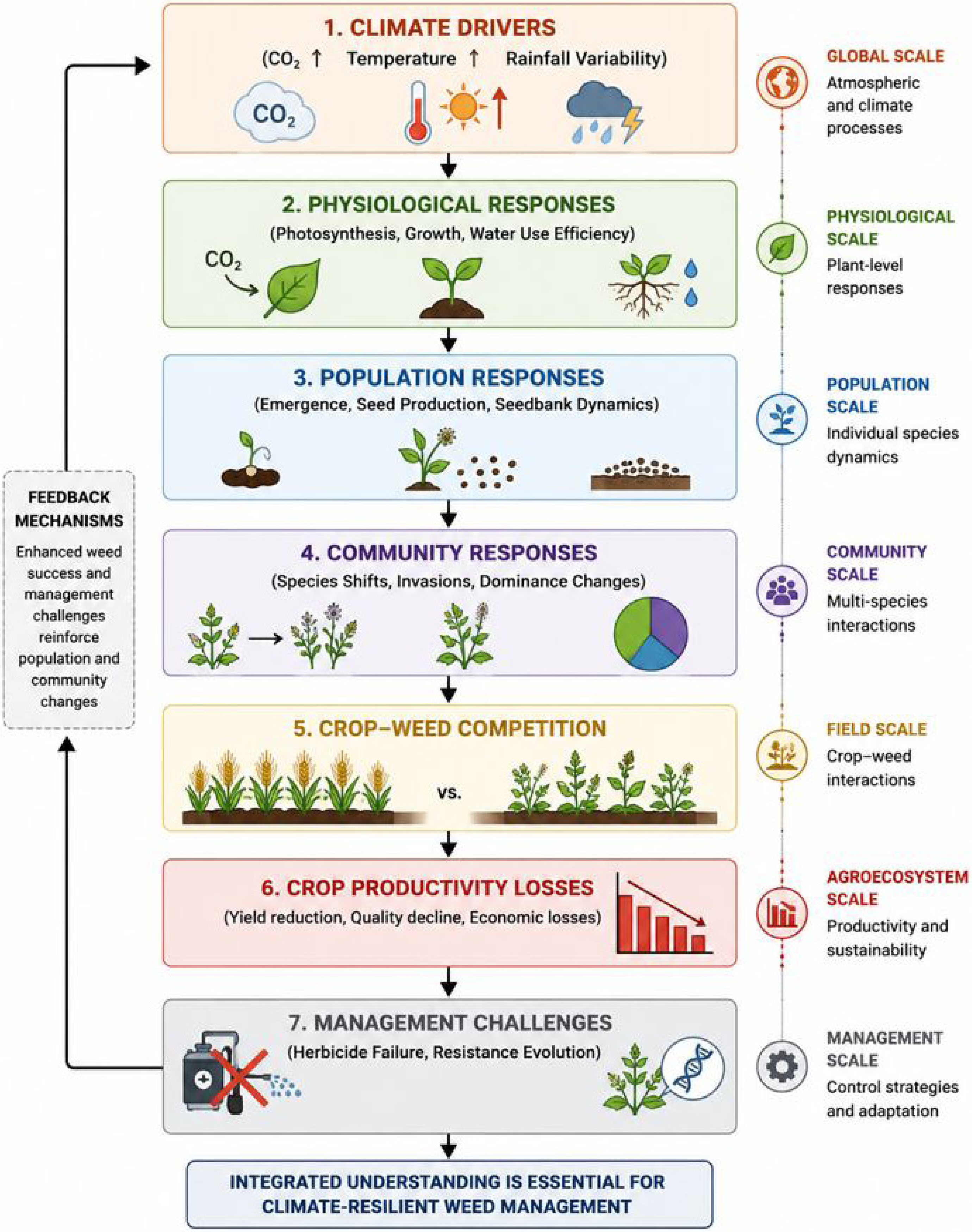

Figure 1: *Conceptual Framework of climate change effects on weed biology and crop production.*

Another principal climatic driver with immediate effects on weed ecology is higher temperatures. Temperature controls key processes like seed germination, metabolic functioning and phenological developments. Warming temperatures may speed up weed life cycles, resulting in earlier emergence, shorter growth periods and higher seed production (Patterson *et al.* 1999). In addition, *Aspergillus* and *Penicillium* species would be promoted under warming conditions, as would C_4 weeds which intrinsically outperform at high temperatures while thermophilic are favored (Dukes, 2011). These changes in species composition may lead to more aggressive and competitive weed communities, especially under heat stress climates that are already prevalent.

Weed dynamics are also complicated more by changes in precipitation patterns, both that of intensity and distribution. Available soil moisture fluctuation controls germination, establishment of seedlings and plant survival (Amare, 2016). Certain weed species exhibit characteristics (e.g., deep rooting systems, dormancy mechanisms) that allow them to survive drought better than crops (Pyšek and Richardson 2010). On the other hand, high rainfall or flooding events can promote the spread of water-adapted weed species and seed dispersal mechanisms. The rise in extreme weather events therefore leads to an increase in temporal and spatial variability of weed populations, which impedes management (Jinger *et al.*, 2017).

Significantly, these climatic drivers interact in complex and frequently non-linear manners. The interaction of elevated CO_2 and temperature may have a greater total weed biomass than would be expected from the effects of these factors in isolation (Ramesh *et al.*, 2017). Likewise, the interaction between temperature and soil moisture can regulate both weed emergence phenology and success, directly modifying crop–weed interactions at critical stages of growth (Sreekanth *et al.*, 2024). These interactions underline the inadequacy of univariate approaches and the necessity for more holistic frameworks to explore responses from weeds under variable climatic scenarios (Elith and Leathwick, 2009).

In addition to their direct effects on weed growth and distribution, climate change drivers also affect the effectiveness of weed management practices. Environmental conditions change plant physiology and chemical behavior that can in turn affect the performance of herbicides (Rao and Korres, 2023). For example, temperature-induced changes in plant cuticle properties and metabolic rates may also influence herbicide uptake and translocation, thereby affecting control under certain environmental conditions (Patterson *et al.*, 1999). Emergence patterns may influence the timely control of these weeds reducing their efficacy and raising the risk of escape (Peters *et al.*, 2014).

Climate-induced shifts in weed distribution and community structure

Climate change is causing broad spatial-scale changes in the distribution and community composition of weed species across agroecosystems. Variations of local temperatures, precipitation rates, and the atmospheric concentration of CO_2 are altering environmental niche space suitability for habitats and subsequently impacting weed geographic range placement (Anwar *et al.*, 2021). Climatic change also effects the range of weeds while some species are extending their distribution into formerly unsuitable areas, and there might even be contraction or local extinction of weed populations (Mahajan *et al.*, 2012). These redistributions are broadly consistent with species-range distributions associated with climate change across plant taxa, i.e. apportioning one population found at a low-locality towards a higher-locality (Parmesan and Yohe, 2003; Walther *et al.*, 2002).

Table 1: *Quantitative responses of weed functional groups to climate change drivers.*

Climate Driver	Weed Response	Reported magnitude	References
Elevated CO_2 (550–700 ppm)	Biomass increase in C_3 weeds	20–70%	Ziska and Dukes (2011); Ramesh *et al.* (2017)
Elevated CO_2	Increased seed production	10–60%	Ziska (2021)
Temperature rise (+2 to +4°C)	Earlier emergence	5–20 days	Patterson *et al.* (1999); Kaur *et al.* (2024)
Temperature rise	Increased reproductive rate	10–40%	Prakash *et al.* (2014)
Drought stress	Competitive advantage of drought-tolerant weeds	Variable (15–50%)	Ramesh *et al.* (2017)
Combined CO_2 + warming	Increased weed competitiveness relative to crops	10–45%	Korres *et al.* (2016); Sreekanth *et al.* (2024)

An example of climate-driven distributional change is the poleward and altitudinal migration of species, which is probably the most well-studied form of climate-driven distributional change (Chandrasena, 2009). Moderating temperatures allow thermophilic weed species to move to higher latitude and elevation where cold stress has previously inhibited their establishment. In agricultural systems, this is especially worrisome because many newly introduced weed species are free from natural enemies and can quickly become invasive (Naidu, 2015). Studies using predictive modeling have shown that climate change is expected to increase the potential range of many harmful weed species, which will exacerbate their impact on crop production and ecosystem stability (Thuiller *et al*., 2005).

Besides range expansion, climate change is modifying the composition and/or structure of weed communities in cropping systems. Changes in environmental conditions may facilitate certain functional groups of weeds over others leading to shifts in species dominance and abundance (Nowak *et al*., 2004). For example, drought prone conditions may favor deep-rooted or stress-tolerant species, while increased rainfall variability could be beneficial for opportunistic and rapidly growing annual weeds. Since weed species often differ widely in both their competitive ability and their growth form, as well as their response to management (Sorte *et al*., 2013), therefore, community composition changes such as those proposed have important consequences for the dynamics of crop–weed competition (Kaur *et al*., 2024).

Extreme weather events have also been emphasized as a mechanism behind climate induced distributional change as it plays an important role in facilitating weed dispersal. Floods, storms and heatwaves in the past may have served as disturbance effects that facilitate seed dispersal along with new opportunities for establishing weeds (Poorter and Perez-Soba, 2001). For example, flooding can disperse weed seeds over long distances naturally, and this can lead to new species being introduced into different agricultural fields; whereas drought conditions may lower the competitiveness of crops and give particular advantage to weeds (Storkey *et al*., 2021). Such episodic disturbances increase spatial heterogeneity of weeds and hasten the community reassembly process under climatic change (Diez *et al*., 2012).

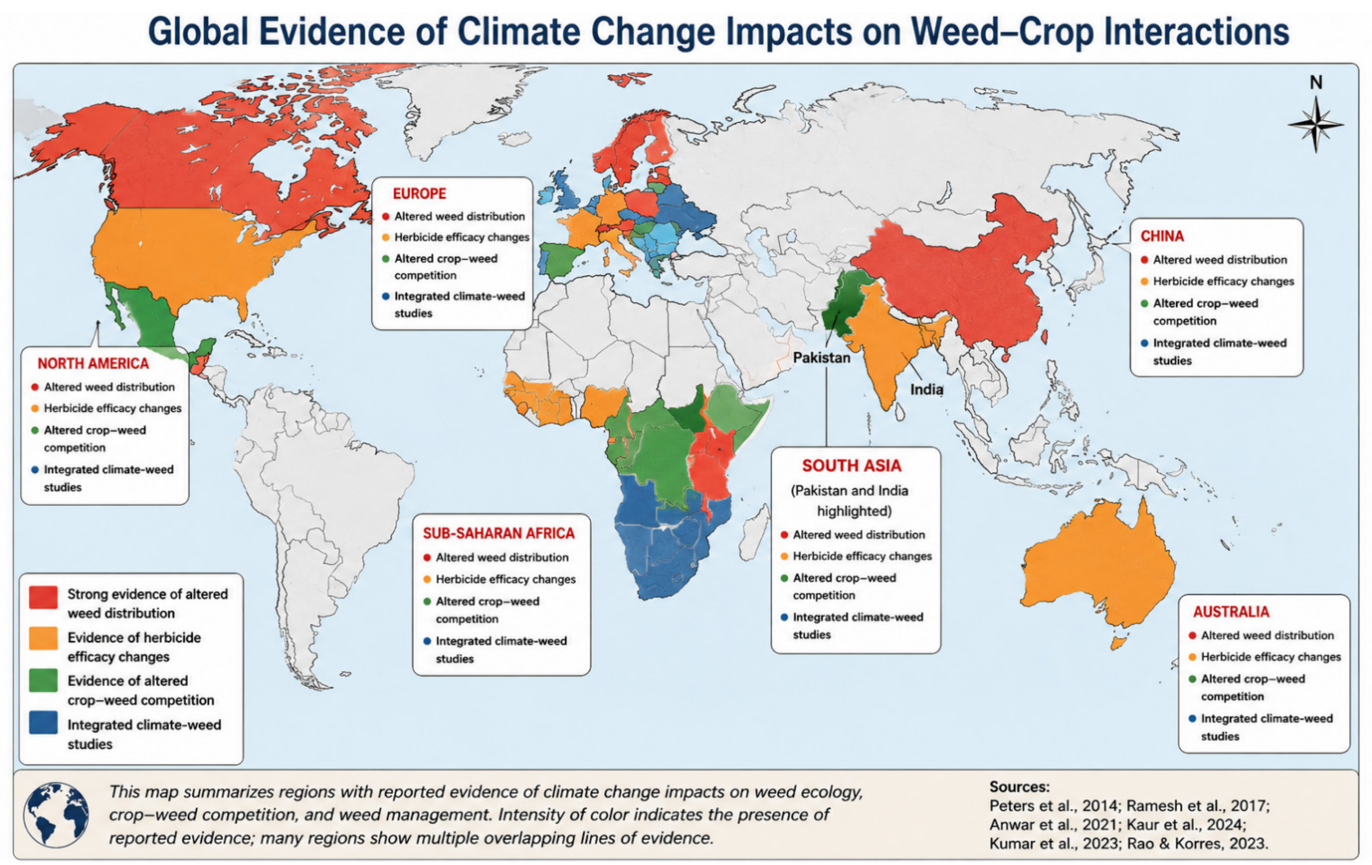

Figure 2: *Global distribution of regions reporting significant climate change impacts on weed ecology, crop–weed competition, and weed management.*

In addition, climate change affects the distribution of species such as weeds via the interaction with anthropogenic factors including land-use change, global trade and agricultural intensification. By moving agricultural commodities and machinery between regions new weed species are introduced and climate change increases the probability of their establishment (Birthisel *et al*., 2021). Under climate drivers and human actions, matched environmental variables become more interconnected globally, increasing the risk of biological invasions by making agricultural weed species establish a wider area and high density more aggressively (Early *et al*., 2016).

Crucially, these shifts in distribution and composition are important not just ecologically but also because they affect agricultural management. Existing control strategies can be rendered ineffectual by introduction of new weed species into cropping systems because management practices are often matched to a particular weed community (Diez *et al*., 2012). And since changes in species composition may also change the timing of weed emergence and growth, it could make scheduling control measures more difficult. Consequently, this may lead to more uncertainty and cost to farmers in weed management as the climate changes.

Weed biology and eco-physiological responses to climate change

Climate change is deemed to be a major driver of physiological responses and adaptive behaviors of weed species at the agroecosystem scale. The germination timing, growth rate, biomass allocation and reproductive output are all mechanisms by which weed species can respond to environmental change (Juroszek and Tiedemann, 2013). The responses are so far driven by increasing concentrations of atmospheric CO_2 (Ainsworth and Long, 2005), environmental warming, and reshuffled water availability; all co-activing changes in plant metabolic activity and ecological fitness (Poorter and Navas, 2003).

Enhanced carbon assimilation through photosynthesis in weeds is the main aspect of weed physiology regulated by higher atmospheric concentrations (Juroszek and Tiedemann, 2013). Although a number of studies have demonstrated the relatively high phenotypic plasticity and resource-use flexibility among weeds compared to crops, whereas both crops and weeds respond positively to elevated CO_2, many studies showed that relative growth responses in increased CO_2 is usually much more positive for associated weed than crop (Prakash et al., 2014). Such advantage is further pronounced in competitive environments where weeds can expand higher carbon towards structural development and reproduction under elevated CO_2 condition (Ainsworth and Long, 2005). These responses can alter competitive hierarchies in ways favorable to weeds, especially when present in mixed C_3 crop–weed systems.

The impact of temperature further alters weed ecophysiology (accelerated enzyme activity, developmental cycles and reproductive rates). In many of our weed species, germination is promoted and seed production is enhanced at higher temperatures, and thus could complete one or more life cycles in a single growing season (Prakash *et al*., 2014). Such observations are particularly important for short-duration annual weeds, as they may respond rapidly to warming with increased density (Sreekanth *et al*., 2024). Warming generally promotes heat-adapted functional groups, especially C_4 weeds, which benefit from relatively high photosynthetic efficiency with elevated temperatures (Naidu, 2015).

Water is the other major determinant of weed physiological responses. Soil moisture regimes are key determinants of seed germination and seedling establishment, and consequently, their dynamics are heavily influenced by changes in rainfall patterns coupled with an increase in the frequency of drought events (Birthisel *et al*., 2021). Compared to many crop species, weed species tend to display a greater degree of drought tolerance owing to deeper rooting system, osmotic adjustment and various dormant strategies of seeds (Ramesh *et al*., 2017). This sort of adaptive trait allows the weeds to keep transpiring under water-scarce environments, increasing their reoccurrence through drought-prone habitats (Sultan, 2000).

These have significant ramifications in semi-arid agricultural regions like Pakistan. Drought-tolerant and fast growing weed species are more competitive under the situation of an increase in temperature due to climate change as the cropping systems of Punjab and Khyber Pakhtunkhwa suffer from heat stress and erratic rainfall, especially during rainy seasons (Anwar *et al*., 2021). These conditions favor the growth of perennial weeds like *Cynodon dactylon* and *Cyperus rotundus* since they survive underground structures from which to regenerate and are also well adapted to prolonged moisture stress (Malarkodi et al., 2017). It makes weed control even harder to achieve in low-input farming systems where irrigation and management adjustments are constrained (Singh *et al.*, 2011).

Climate change weed ecophysiology is another aspect of simultaneous multiple environment drivers. Effects of concurrent elevated CO_2, temperature and water stress often induce results that are non-linear and synergetic on weed growth and competitiveness (Argenta, 2020). For instance, it is expected that elevated CO_2 improves water-use efficiency partially compensating for drought stress and increasing biomass accumulation at the same time. Moreover, if warming temperatures speed development to an extent that offsets the benefits of CO_2-induced growth (Pritchard *et al.*, 2006), a more complex and species-dependent outcome is possible.

Weed reproduction and evolutionary potential are also affected by climate change. A lot of weeds demonstrate fast adaptive evolution and try to regulate quickly in the transforming environment (Argenta, 2020). Under variable climatic conditions, the most frequently selected traits are early flowering date, increased number of seeds produced by the crop, and an extended seed dormancy cycle. This evolutionary plasticity allows weeds to survive all sorts of environments and also plays a role in their success as invasive species within disturbed agroecosystems (Walther *et al.*, 2009).

Crop–weed competition under climate change

Crop weed competition is one of the most direct ways through which climate change impacts agricultural productivity. Crop weed competition basically occurs due to their simultaneous requirement of limiting resources like light, water, nutrients and space. Climate change affects these interactions through changes in resource availability, plant physiology and weed germination patterns that have the potential to shift competitive outcomes in agroecosystems (Das *et al.*, 2012). Lately, the competition balance has shifted toward weeds as they have higher ecological plasticity to adaptive capacity and face fewer these selective changes with changing environmental conditions (Zimdahl and Basinger, 2024; Swanton and Weise, 1991).

The differential response of C_3 and C_4 species is one of the key mechanisms impacting crop–weed competition under higher atmospheric CO_2. Higher CO_2 usually promotes photosynthetic capacity in C_3 crops such as wheat, rice, and barley; however, numerous weed species are also C_3 which could exhibit substantial greater relative growth responses than crops through their higher phenotypic plasticity (Ziska and Dukes, 2011). For example, C_4 weeds might already be so efficient there that warming would favor them much more than CO_2 enrichment (Ainsworth and Long, 2005; Ziska and Dukes, 2011), producing complex competitive hierarchy shifts.

Higher temperatures further enhance the crop–weed competition by increasing growth rates and shortening life cycle of weeds. Crops typically take longer to respond to warming than weeds, resulting in faster emergence of non-crop canopy earlier in the growing season. With this early head start, weeds can outcompete crops for resources (especially light) during crucial vegetative stages of crop establishment. Significant and irreversible yield loss due to early-season weed interference can occur after short durations of competition (Cousens, 1985; Zimdahl and Basinger, 2024). Under climate warming scenarios this important phase of weed interference is expected to advance and intensify.

Evidence from crop–weed competition studies suggests that climate warming may reduce the critical period for weed control by approximately 10–30%, although the magnitude varies among crops and weed communities (Prakash *et al.*, 2014). The reduction appears to be largely associated with accelerated weed emergence and growth rates under warmer conditions, enabling weeds to reach competitive thresholds earlier in the season. Current evidence indicates that this response is often nonlinear, with relatively modest changes occurring under moderate warming but substantially larger shifts occurring when temperature increases coincide with moisture stress and elevated atmospheric CO_2 concentrations (Pritchard *et al.*, 2006). Such findings suggest the possibility of threshold-type responses rather than simple linear relationships.

Precipitation patterns are also pivotal in reshaping crop–weed competition. Weeds can show higher drought tolerance than crops in rain-scarce environments, such as arid and semi-arid regions.

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Weeds have deeper root systems, osmotic adjustment and seed dormancy that allow continued growth under moisture stress. Consequently, drought conditions often decrease competition for crops, while simultaneously benefiting adaptation of weed species to drought and therefore enhancing competition for limited soil moisture (Olesen and Bindi, 2002; Ramesh *et al*., 2017).

These dynamics become much more marked in Pakistan because of the predominantly irrigated and rainfed mixed cropping systems. Punjab and Khyber Pakhtunkhwa wheat-based systems are prone to heat stress, uneven rainfall plus lower soil moisture availability. Such conditions enable highly competitive weed species like *Phalaris minor, Cynodon dactylon and Chenopodium album* to severely limit wheat productivity by competing with it for moisture and nutrients during early growth stage (Nawaz *et al*., 2026). Weed-induced yield losses in wheat without management are estimated to be over 30–40% of potential ci, depending on the circumstances (Ain *et al*., 2016; Sardana *et al*., 2017), a problem aggravated by climate variability in South Asian agroecosystems. (Ramesh *et al*., 2017).

Diversity of climate-altered competition another key dimension is the change in timing and synchrony between crops and weeds. Germination cues can be altered by climate warming, causing split emergence patterns. If weeds emerge prior to the crop, they gain a competitive advantage by monopolizing resources before the closure of crop canopy. Fostering such asymmetric competition is projected to become more common in most future climate scenarios, especially in systems with simplified rotations and reduced tillage (Knezevic *et al*., 2002; Korres *et al*., 2016).

This dynamic competition is compounded under elevated CO_2 by changing resource-use efficiencies. Weeds often respond more aggressively to increased CO_2 than crops do, since they grow with greater plasticity while allocating more resources to vegetative structures. This may promote more weed biomass in crop treatments with crop yield stimulation (Poorter and Navas, 2003) which could translate to a net competitive disadvantage for crops over time, especially in mixed communities. In addition, soil nutrient limitations due to climate change can increase competition between crops and weeds because many weed plants have the potential to use resources of soils (e.g., nutrients) more rapidly than crops when fertilizer levels are low.

Climate change and the role of weeds in affecting crop productivity

Weeds are still one of the biggest biological barriers to global agricultural production that they have direct and indirect effects on crop yield, quality and stability of production. It has been estimated globally that weeds have led to significant yield losses in all major staple crops, including wheat, rice, maize and soybean species due in large part to competitive losses of light, water and nutrients during critical growth stages (Ali and Afzal, 2026; Chauhan *et al*., 2026). Recent assessments verify that although it has overcome remarkably by herbicide technology and agronomic practices, weed-associated yield losses keep growing with the passage of time in many regions induced by environmental change (Maity *et al*., 2026; Muneret *et al*., 2026).

Climate change is exacerbating the effects of weeds on crop productivity through increased rates of weed growth, longer growing seasons and changing patterns in competition between crops and weeds (Zwetsloot *et al*., 2026). In many mixed systems, particularly where weeds exhibit a high degree of phenotypic plasticity (Benvenuti and Baldoni, 2026), atmospheric CO_2 and temperature generally stimulate weed biomass production much more than crops. This reduces in-crop competition during the most yield-damaging time of the crop–weed interaction cycle, early-season. Research shows that even transient weed presence in early crop growth has been linked to irreversible yield penalties (Kubinski *et al*., 2026) and especially if the crop is a cereal-based system.

Further yield losses can occur from the combined effects of accelerated weed germination and growth compared with crops as temperature rises. Indeed, weeds can be observed to establish earlier canopy dominance under warmer conditions than crops, limiting light availability for the crop and inhibiting biomass accumulation (Whitnall and Beatty, 2026). Experimental and modeling studies suggest that warming increases weed growth rates as well as reduces the critical period for weed control, resulting in more challenges to timely management and higher seasonal yield variability (Alejo *et al*., 2026; Guo *et al*., 2026).

As a second major pathway, weeds induce crop productivity loss under climate change through water stress. Weeds are often more tolerant to drought than crops in water-limited environments as they frequently have deeper rooting systems and better strategies for using scarce water (Arvin *et al*., 2006). Weeds continue to dominate under moisture stress with disproportionate yield penalties in rainfed systems, as rainfall frequencies become more erratic. In South Asia, the variability in monsoons is a critical determinant of not only weed emergence but also crop productivity (Nawaz *et al*., 2026) and thereby makes this effect significant for STBP.

Weed pressure is one of the most important limiting factors for wheat-based cropping systems in Pakistan, which are the cornerstone of national food security. Yields are drastically reduced in fields infested with weeds like *Phalaris minor*, *Avena fatua* and *Chenopodium album*, especially under conditions of delayed sowing and heat stress (Nawaz *et al*., 2026). Data reached in the past years of agronomic evaluations show that uncontrolled weeds can cause wheat yield losses greater than 30%, and if climate variability is present, weed aggressiveness concomitant with diminished competitiveness of crop will aggravate losses (Ain *et al*., 2026; Loddo and Sattin, 2026).

Climate change can also amplify spatio-temporal variability in weed impacts on crop productivity (Shah *et al*., 2026). Fluctuations of temperature and rainfall have also been reported to cause irregularity in the emergence of weeds, thus causing an uneven intensity of competition pressure throughout seasons and regions (Gebretsadik and Kayombo, 2026). This variability leads to more unpredictable yield outcomes and a failure of existing crop productivity models. Recently, the literature emphasizes that climate variability not only increases average yield loss but inter-annual instability of crop production systems (Thapa *et al*., 2018).

Another crucial aspect is indirect impact of weeds on crop quality. Weeds may compete with crops at reproductive stages, shortening spikelet and seed filling periods which can subsequently impact grain size (Ekanayake, 2026), protein content and as a consequence, overall market value. Also, weeds are one of the alternative hosts for insect pests and plant pathogens that can exacerbate crop losses under climate-stressed conditions indirectly (Baiswar *et al*., 2026). These multi-faceted impacts lead to weeds being a significant limitation both on crop yield potential as well as quality and ultimately food security.

The magnitude and direction of climate-mediated weed impacts are strongly influenced by regional variability. In temperate regions, warming typically stimulates the poleward shift of thermophilic species and lengthens growing seasons, whereas in tropical and subtropical areas it is often accompanied by drought stress or changes to rainfall regimes (Kaur *et al*., 2024). South Asian cropping systems, particularly in Pakistan and India, are most vulnerable because climate stress commonly occurs alongside high weed pressure, late sowing, or insufficient water. Conversely, studies from Europe and North America frequently highlight species range shifts and resistance evolution (Ekanayake, 2026). While the overall mechanisms are largely consistent across regions, climate-driven interactions between weeds and crops may vary in intensity, and management responses may differ due to local agro-ecological conditions.

Weed management and herbicide efficacy under climate change

The predominant approach to weed management in modern agriculture is through herbicides, but their effectiveness is increasingly threatened by climate change-mediated changes in environmental conditions. The performance of herbicides is not only dependent on their chemical properties but changes in temperature, atmospheric CO_2 concentration, soil moisture and humidity (Sreekanth *et al*., 2023). This is supported by recent literature that shows aspects of these same climatic conditions are changing the way in which weeds uptake, translocate and metabolize herbicide making chemical control systems in the field less predictable (Ziska, 2016).

Higher atmospheric CO_2 changes most of the weed physiology relative to herbicide sensitivity. While the increased CO_2 may stimulate plants to grow thicker cuticles or reduce stomatal density, and alter other characteristics of the leaf surface that restrict herbicide absorption (Siddiqi *et al*., 2021). More broadly, accelerated carbon fixation at elevated concentrations of atmospheric CO_2 increases the metabolic potential of weeds enabling fast recovery following post-emergence sub-lethal herbicide exposure. Indeed, experimental evidence shows that these physiological alterations could decrease the efficacy of some systemic herbicides over other weed species exposed to a combination of CO_2 and temperature stress (Sondhia *et al*., 2024).

Another key factor to consider when making herbicide decisions, is that of temperature rise. Higher temperatures lead to faster herbicide volatilization and degradation, providing less active ingredient to reach the target weed (Kaur *et al*., 2024). At the physiological level, temperature rises can accelerate enzymatic detoxification pathways present in weeds allowing for a more rapid metabolism of herbicides leading to reduced efficacy. It has been shown in a number of recent field studies that under conditions of heat stress herbicides can be highly variable in their performance with high-temperature regimes leading to large reductions due to application (Rao and Korres, 2023). This is especially true for warm regions like South Asia, where peak cropping seasons increasingly overlap with heat stress events.

This variability in soil moisture complicates the performance of herbicides even more. Most pre-emergent herbicides require moisture in order to activate and be taken up by the soil, thus the drought greatly reduces their efficacy (Kumar *et al*., 2023). On the other hand, too much rain can wash herbicide below the zone in which weeds germinate and lead to inadequate controls. Various modeling studies show that the effectiveness of herbicide-based weed control systems is expected to be compromised in rainfed agricultural systems under future climate scenarios with increased rainfall variability (Ramesh *et al*., 2017).

They are increasingly visible in the major cropping systems of Pakistan particularly wheat–rice and wheat–cotton rotations. In Punjab and Khyber Pakhtunkhwa, farmers claim that herbicides have shown variable efficacy against troublesome species like *Phalaris minor and Chenopodium album* under variable irrigation stress and temperature (Nawaz *et al*., 2026). These contradictions have been attributed not only to resistance problems but also climate-induced alterations in herbicide behavior and weed physiology (Matzrafi, 2019).

A new yet urgent issue is the evolution of herbicide resistance under climate change. High CO_2 and drought are both environmental stressors that can enhance the survival rates of weeds exposed to sub-lethal doses of herbicides, thus increasing selection pressure for resistant biotypes (Ali and Afzal, 2026). In fact, it magnifies herbicide resistance evolution in certain cropping systems often seen with low diversity high input intensive systems. Recent studies indicate that variation in climate may indirectly promote the evolution of resistance by amplifying the occurrence of herbicide failure events (Rout and Raul, 2026).

Climate change also shifts weed emergence timing and herbicide use efficiency. Additionally, increased temperatures and changed rainfall patterns may result in asynchronicity of weed germination that shifts peak periods of weed susceptibility to herbicides away from the normal herbicide application windows (Gagliardi *et al*., 2026). This phenological mismatch is becoming acknowledged as one of the greatest drawbacks of traditional weed management systems, especially those that depend upon fixed-schedule herbicide applications (Zeidali, 2026).

Recent studies also propose frameworks for predicting herbicide performance under changing climate, including variables like temperature, soil moisture, CO_2 levels, and weed growth stages (Bhatacharjee, 2019). Temperature and soil moisture are key factors affecting herbicide uptake and persistence (Jinger *et al*., 2017). Although field-validated models are limited, evidence suggests climate and biological variables can be integrated into decision-support systems to improve herbicide timing under future conditions.

To tackle these challenges recent studies advocate shifting towards Integrated Weed Management (IWM) systems. Integrated Weed Management (IWM) is a combination of chemical, mechanical, cultural and biological methods that seek to promote systemic resistance against climatic uncertainty while reducing dependency on herbicides (Ekanayake, 2026). The importance of rotating crops and varieties, selection of competitive crop cultivars, super-imposing new sowing dates and implementation of precision application technologies are becoming more recommended to protect weed control in a variable changing environment (Bhattacharjee, 2019).

Table 2: *Climate variables influencing herbicide efficacy and weed management.*

Climate variable	Effect on weed physiology	Consequence for herbicide performance	References
Elevated CO_2	Thicker cuticle, reduced stomatal density	Reduced herbicide uptake	Matzrafi (2019); Kumar *et al*., (2023)
High temperature	Increased metabolism and detoxification	Reduced herbicide persistence	Sreekanth *et al*., (2024)
Drought stress	Reduced growth rate and translocation	Lower systemic herbicide efficacy	Kumar *et al*. (2023)
Excess rainfall	Herbicide leaching and runoff	Reduced residual activity	Sondhia *et al*. (2024)
Variable emergence timing	Asynchronous weed populations	Mistimed applications	Rao and Korres (2023)

Climate-resilient weed management: Research gaps and future directions

Areas like climate change impacts on weed ecology and crop–weed interactions are being increasingly researched, but significant knowledge gaps exist that impede the design of effective predictive and adaptive weed management strategies. One of those main limitations is the absence of long-term studies in situ, which now do not compare multiple climatic drivers (including an elevated CO_2, temperature rise and precipitation variability) simultaneously at a realistic agroecosystem level. The majority of existing evidence comes from experiments designed in highly controlled environments which so often do not reflect field level complex interactions and the variability arising from different management approaches (Reumaux *et al*., 2026).

Their research also highlighted an important gap regarding the understanding of weed adaptive evolution in the context of climate change. As weed species harbor high levels of genetic plasticity, it is appreciated that empirical data on interactions between climate-driven selection pressures with herbicide resistance evolution and ecological adaptation (Sabharwal and Reddy, 2026) is still lacking. While these observations suggest that climate variability may promote more rapid evolution in weed populations, few examples exist of quantitative field validation across diverse agroecological zones (Kniss *et al*., 2016). Such scenario is particularly relevant for regions like South Asia, where both heavy herbicide use and climate stressors occur.

Similarly, transparent, high resolution regional weed distribution models that build in climate projections are also lacking in Pakistan and comparable developing agricultural systems. Current models are largely global or continental, and show major shortcomings in reflecting local variability within cropping systems, irrigation practices and soil conditions relevant for decision making. Such localized predictive modelling is a prerequisite for effective weed management planning based on projected climatic scenarios, given the heterogeneity of Pakistan's agroecological zones from irrigated Punjab to rainfed Khyber Pakhtunkhwa (Abbas and Arshad, 2026).

Integrative modeling approaches (i.e., crop physiology, weed ecology and climate projections) will be warranted by future research. However, mechanistic crop–weed competition models under climate scenarios that factor in phenological coincidences and resource-use efficiency might still be woefully inadequate (De Ponti *et al*., 2012). Predictive accuracy may be improved by trait-based approaches (Kumar *et al*., 2023) although research frameworks are still in early application stages in weed science (Shao *et al*., 2026).

A second major area is promoting climate-resilient integrated weed management (IWM) systems. The use of only herbicides has become a less sustainable option due to their reduced effectiveness in the context of climate variability and accelerating evolution of resistance. Current approaches highlight a range of management strategies (e.g. crop rotation, competitive cultivars, modified sowing dates, precision agricultural technologies) needed to mitigate the impact of changing environmental conditions on weed control (Chaudhary *et al*., 2026; Geddes *et al*., 2026). South Asian systems, especially Pakistan's wheat-rice and wheat-cotton rotations, urgently need such integrated approaches to sustain productivity.

A further implication of changing climate is that the existing patterns of weed emergence and critical periods of interference will change (Nawaz *et al*., 2026), which redefines traditional timings for weed control. Recent research on changing climate conditions and the shift in windows of weed emergence (Ekanayake, 2026) challenges the idea of a static critical period for weed control. However, the real-time response of weed–crop interactions to climatic variability in this dynamic (and notorious) system will require adaptive management strategies that are not based on a fixed calendar approach, but can respond as climate changes over time (Yang and Chen, 2026).

While thresholds vary across cropping systems and weed species, recent research suggests multiple climate-related tipping points could cause failure in several weed management strategies. Long droughts, repeated heatwaves during crop growth, and persistent herbicide pressure will raise management failures. Under these conditions, crops become less competitive while stress-adapted weeds thrive (Walther *et al*., 2002).

Studies show management effectiveness may decline disproportionately after certain climate thresholds. Prolonged heat stress can weaken crops, alter weed emergence, and reduce herbicide effectiveness. Droughts impair crop establishment, promote drought-resistant weeds, and lower herbicide activation. These combined pressures can cause failures across physiological, ecological, and management levels, requiring multiple adaptation strategies instead of single interventions (Sreekanth *et al*., 2023).

In conclusion, these predictions of change point the way towards a predicted or adaptive systems for future weed management in the future under climate change rather than reactive control. This entails the combining of remote sensing and machine learning, climate forecasting tools with agronomic decision making. In regions like Pakistan, where smallholder farmers are resource-limited and the climate is highly vulnerable, deploying affordable and context-specific weed management solutions will be central to maintaining agricultural productivity.

Conclusion

Climate change is radically changing the relationships between weed and crop species in agricultural systems globally, with broad consequences for food security and farm viability. Increasing CO_2, temperature and changing precipitation patterns are together driving changes that will improve the competitiveness of weeds through faster growth, altered phenology and enhanced stress tolerance. Consequently, weeds are increasingly impinging on crop productivity by means of intensified competition for resources, but also through reduced effectiveness and reliability of already existing weed management strategies. Internationally these shifts are driving yield loss in major staple crops, and especially in cereal-based production systems where weed interference early in the season has become more challenging to manage.

Globally, agriculture is at a stage where climate variability is making the established weed management practices less predictable. The performance of herbicides is becoming increasingly variable with the season, because changes in environmental factors within and between growing seasons modify the uptake and metabolism of herbicides, while the combined ecological and climatic stress arising from climate change accelerates resistance evolution. This has meant that single-mode weed control strategies are no longer sustainable. Instead, it has been a consensus towards holistic weed management systems that integrate chemical and cultural defence along with mechanical and technological fights to ensure long-term profitability in agriculture despite changing climatic conditions.

These challenges are particularly evident in the case of Pakistan as it is a country that has high climatic sensitivity and is heavily reliant on wheat based cropping systems. Increases in temperature, erratic monsoon rainfall distribution and lack of irrigation availability is increasing the intensity of weed pressure on both irrigated and rainfed agriculture. Under delayed sowing and heat-stressed conditions, competition of *Phalaris minor, Avena fatua and Chenopodium album* as perennial fallow is increasing. Together these factors are driving substantial yield volatility in key crops, with wheat (the one crop most critical to national food security) amongst the worst impacted. Furthermore, the vulnerability of weed impacts associated with climate changes is amplified due to inadequate mechanization, smaller landholding size and an inordinate reliance on herbicides.

In the immediate future, sustainable agricultural productivity in Pakistan and other vulnerable regions will demand a transition from responsive weed health measures to climate-resilient proactive weed management strategies. For example, this includes integrating crop diversification with competitive cultivars and optimal planting dates, precision agriculture tools where they exist and the specific use of herbicides that are required. The need for the research of weed ecology under local climate scenarios is also important for building future predictive and adaptive-management strategies. At the end of the day, tackling climate change under weed-induced yield losses is not only an issue of agronomic efficiency; it represents a substantial challenge in long-term global food security within our already warming and increasingly variable global climate.

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Novelty Statement

This review integrates climate-driven physiological, ecological, and management changes in weed–crop interactions into a multi-scale framework, highlighting region-specific vulnerabilities and the limitations of current weed management under rising CO_2, warming, and rainfall variability.

Author's Contribution

Iqtidar Hussain: Principal investigator, collected and compiled relevant literature.
Sheheryar: Conceptualized the review topic and wrote the entire manuscript.
Mohammad Safdar Baloch: Critically refined, edited, and improved the manuscript's scientific coherence and language.
Muhammad Zubair Khan: Contributed to structuring the review and provided intellectual guidance and final approval of the manuscript.

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