



Review Article

Weed Dynamics and Management under Climate Change in Iran: A Comprehensive Review

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Abstract

Climate change has emerged as one of the most prominent and recognizably important environmental factors driving agronomic change in Iran. Climate change has modified the dynamics and the management of weeds; specifically, Iran's arid and semi-arid agroecosystems are increasingly subjected to more extreme temperatures and reduced precipitation, including more frequent droughts, as well as atmospheric CO₂ concentrations. These changes have increased the distribution of thermophilic and drought-tolerant weed species, modified the composition of weed species, and enhanced weed growth, seed production, and competitiveness in interactions with important crops. Traditional crops, including crops like wheat, rice, and maize, are being increasingly subjected to negative effects on crop yields. Further, the various weed species becoming increasingly invasive and flexible in their response to climate change, while the traditional management techniques used for weeds is being challenged. Chemical control is being challenged by changes to plant physiological processes, less effective herbicide application due to elevated CO₂ conditions, rapid evolution of weed resistance, and environmental consequences of weather and climate such as dust storms and freezing. Mechanical weed management is being challenged because of less than synchronous germination rates, increased below ground biomass, as well as moisture extremes in the soil. Biological control is being challenged by life cycle timing discrepancies for the target weed, and a decrease in host specificity by biological control agents. All these factors are expected to produce yield declines of 5-25% by 2050 and worsen food security issues. Integrated Weed Management (IWM) appears to be the best way forward by blending climate-resilient cultivars, diversified crop rotations, cover cropping, precision agriculture technology (GIS, UAVs, decision-support tools), and conservation agriculture. Farmer education, long-term monitoring, and adaptive policy support will be needed. It was concluded that moving forward only through a proactive, holistic approach combining ecological principles with technological innovation, and institutional support will Iran be able to create resilient agroecosystems that can produce under climate change.

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مقاله مروری

مروری بر پویایی و مدیریت علف‌های هرز در ایران، در عصر تغییر اقلیم

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چکیده

تغییر اقلیم به عنوان یکی از مهم‌ترین عوامل زیست‌محیطی مؤثر بر تغییرات زراعی در ایران مطرح شده است. این پدیده پویایی و مدیریت علف‌های هرز را نیز دگرگون کرده است، به‌ویژه در نظام‌های کشاورزی خشک و نیمه‌خشک ایران که با افزایش دما، کاهش بارندگی، خشکسالی‌های مکرر و افزایش غلظت دی‌اکسیدکربن اتمسفری، مواجه هستند. این تغییرات موجب گسترش گونه‌های علف‌هرز گرمادوست و مقاوم به خشکی، تغییر در ترکیب گونه‌ای علف‌های هرز، و افزایش رشد، تولید بذر و رقابت‌پذیری آن‌ها در مقایسه با گیاهان زراعی اصلی شده است. گیاهان زراعی عمده مانند گندم، برنج و ذرت تحت تأثیر منفی این شرایط قرار گرفته و عملکرد آن‌ها کاهش یافته است. گونه‌های علف‌هرز نیز تهاجمی‌تر و سازگارتر شده‌اند، درحالی‌که روش‌های سنتی کنترل علف‌های هرز کارایی خود را از دست داده‌اند. کنترل شیمیایی با چالش‌هایی مانند تغییر فرایندهای فیزیولوژیکی گیاهان، کاهش اثربخشی علف‌کش‌ها در شرایط افزایش دی‌اکسیدکربن، تکامل سریع مقاومت به علف‌کش‌ها و اثرات زیست‌محیطی ناشی از پدیده‌هایی چون طوفان، گردوغبار و یخبندان مواجه است. کنترل مکانیکی نیز به دلیل عدم هماهنگی در زمان جوانه‌زنی، افزایش زیست‌توده زیرزمینی و نوسانات رطوبتی خاک با محدودیت روبه‌رو است. کنترل زیستی نیز به علت عدم تطابق زمانی چرخه زندگی عوامل کنترل با علف هرز هدف و کاهش تخصصی‌بودن میزبان در عوامل زیستی مؤثر، با مشکل روبه‌رو شده است. این عوامل به‌طور کلی می‌توانند منجر به کاهش عملکرد محصولات زراعی بین ۵ تا ۲۵ درصد تا سال ۲۰۵۰ شده و امنیت غذایی را تهدید کنند. در این میان، مدیریت تلفیقی علف‌های هرز به عنوان راهکاری مؤثر مطرح است که با ترکیب ارقام مقاوم به اقلیم، تناوب زراعی متنوع، کشت گیاهان پوششی، فناوری‌های کشاورزی دقیق مانند GIS، پهپادها و ابزارهای تصمیم‌یار و نیز کشاورزی حفاظتی می‌تواند کارایی مدیریت علف‌های هرز را افزایش دهد. آموزش کشاورزان، پایش بلندمدت و حمایت‌های سیاستی تطبیقی، از الزامات موفقیت این راهبرد است. در نهایت، تنها از طریق رویکردی جامع و پیش‌آگاهانه که اصول بوم‌شناسی را با نوآوری فناورانه و حمایت‌های مؤسسات، تلفیق کند، می‌توان نظام‌های زراعی ایران را در برابر تغییر اقلیم مقاوم ساخته و پایداری تولیدات کشاورزی را تضمین کرد.

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حق انتشار این مستند، متعلق به نویسندگان است. © ۱۴۰۴. ناشر این مقاله، انجمن علوم علف‌های هرز ایران و موسسه تحقیقات گیاهپزشکی کشور است. این مقاله تحت گواهی زیر منتشر شده و هر نوع استفاده غیرتجاری از آن مشروط بر استناد صحیح به مقاله و با رعایت شرایط مندرج در آدرس زیر مجاز است.



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Introduction

Climate change is an important factor in ecological and agronomic change in arable ecosystems (Pautasso et al., 2010). Changes in temperature, precipitation, and with extreme events, change the weed assemblage, ranges, and competitiveness of weeds (Peters et al., 2014; Walther et al., 2002). Climate driven shifts in the context of dryland agriculture are impacted by both abiotic factors arising from climate change (e.g., atmospheric CO₂ increase, warming) and indirectly by rainfall and plant management responses to climate change (e.g., sowing dates, crop rotations, irrigation) (Fleming & Vanclay, 2010; Olesen & Bindi, 2002). Species composed of thermophilic weeds (i.e., *Amaranthus retroflexus*, *Abutilon theophrasti*) and broad C₄ weeds (e.g., *Setaria* spp., *Sorghum halepense*) are increasingly moving northward (Weber & Gut, 2005; Hanzlik & Gerowitt, 2012; Salonen et al., 2013), while ubiquitous and “upstarter” weed species are increasingly becoming dominant in disturbed systems (Peters et al., 2014).

Weeds–climate change interactions manifest in a nested relationship across scale, range, niche, and traits, (Peters et al., 2014) and there are important factors above the range shift including altered interactions between species, phenological shifts, and herbicide resistance that need to be meta- analyzed (Neve et al., 2009), even if only descriptive rather than causative. Weeds establish earlier and elongate crop growth, making them harder to manage as well as exposing crops and relatives to CO₂ increases (Ziska, 2003). Climate stresses have produced more invasive weeds through polyploidy, hybridization and selection (Clements & Jones, 2021). Adaptive integrated weed management (IWM) should decrease dependency on herbicides after developing

IWM systems that consider climate smart practices such as diverse rotations, cover crops, and precise tillage (Booth & Swanton, 2002). Undertaking long-term monitoring weed characteristics provides farmers a proactive approach in managing weeds with climate change. This review outlines concerning climate-related shifts in weed dynamics across Iran, the potential impact of these changes, the associated risk of adaptive strategies, and the notions of ecological sustainable weed management.

Climate Change and its effect on Iran

Climate change is defined as human-induced changes in the atmosphere beyond natural variability (NCCOI, 2014), which primarily refers to greenhouse gases (CO₂, CH₄, and N₂O) resulting from fossil fuel combustion and deforestation (IPCC, 2014; IPOC, 2001; Killman, 2008). The Intergovernmental Panel on Climate Change (IPCC) takes a broader view that includes both natural and human-induced changes (IPCC, 2014). Global warming is of significant concern in climate change discussions, as the Earth's surface temperature is now ~1.1°C higher than it was in preindustrial times due to a higher amount of radiative forcing (IPCC, 2014). Climate change, especially global warming, is distinct from short-term variability of temperature from events such as an El Niño, and volcanic eruptions that may change the long-term temperature record (Trenberth, 2011), as climate models use Representative Concentration Pathways (RCPs) to project future climate possibilities (IPCC, 2014) on agriculture and weed populations/management (Ramesh et al., 2017; Amare, 2016).

Table 1. Key impacts of climate change on Iran (Based on [Mansouri Daneshvar et al., 2019](#))

Category	Indicator / Variable	Climate Change predictions
Temperature	Mean annual temperature	Projected increase of 2.6 °C in the coming decades Observed significant rise in both minimum and maximum temperatures
	Heat waves	Frequency of heat waves expected to increase by ~30% by the end of the century- 66% of Iran shows a significant positive trend in hot days and nights.
	Cold extremes	Significant decrease in cold days (40.9%) and cold nights (68.5%) across the country.
Precipitation	Annual rainfall	35% decline in precipitation projected in the coming decades Observed decreasing trend at a rate of 2.56 mm/year over the past 40 years.
	Seasonal distribution	Greatest reduction in winter precipitation
	Extreme events	Decrease in frequency of extreme precipitation events Increased risk of droughts; reduced flood magnitude.
Snow Cover	Snow extent and duration	Significant decreasing trends in snow cover across Iran Projected continued decline by the end of the 21st century due to rising temperatures.
Surface Energy Balance	Upward Longwave Radiation (ULR)	Significant increase in ULR during both winter and summer Reflects rising surface heat and atmospheric warming

Iran, which is positioned in the subtropical arid and semi-arid geographical belt, is particularly vulnerable to climatic change. Approximately 85 percent of the country can be classified as arid or semi-arid, and available data indicates that both temperature and winter precipitation is likely to decrease. Increased heat will magnify upward long-wave radiation ([Mansouri Daneshvar et al. 2019](#), Table 1). By the middle of the 21st century, it is projected that temperatures in Iran will increase by ~2.6°C while precipitation will decrease by 35 percent, leading to drought conditions with severe implications for agricultural production and water security in the country ([Mansouri Daneshvar et al., 2019](#), [NCCOI, 2014](#), [Shahbazi & De La Rosa, 2010](#), [Saymohammadi et al., 2017](#)). Heatwaves could also increase by 30 percent, particularly in central and southern Iran ([Zhang et al., 2005](#), [Rahimzadeh et al., 2009](#)). While significant mountain ranges such as Zagros and Alborz hinder rainfall and significantly alter microclimates, there is an overall reduction in moisture conditions particularly in the northwest and southeast of the country ([Modarres & Sarhadi, 2009](#)), further compounding vulnerabilities for Iran's water resources and agroecosystems.

Effects of Climate Change on Agriculture in Iran

Climate change represents a significant challenge to agriculture and food security throughout Iran. Regionally based assessments confirm warming, declining precipitation, and more droughts and heatwaves. Importantly, both spatially and temporally these changes are highly variable because of mountain ranges such as Alborz and Zagros ([Dinpashoh et al., 2004](#); [Modarres & Sarhadi, 2009](#); [Tabari & Talaei, 2011](#)). One major change that is consistent is the rise in the mean annual temperature, which has been much higher and more pronounced in arid and semi-arid farmlands, yielding early springs, longer growing seasons, but also greater evaporative demand and pulling moisture from both rain-fed and irrigated systems ([Raziei et al., 2012](#)). For example, in northern Iran, the agriculture reliant upon the Caspian moistures are experiencing declines in year-round precipitation, with serious impacts on high-water use crops ([Tabari & Talaei, 2011](#)).

Nationwide, across the country, dwindling precipitation and the transition to fewer storms that deliver precipitation but provide more intense rains are yielding bigger runoff, more

soil erosion, and a decrease in surface aquifer water recharge (Raziei et al., 2012).

All of these shifts lead to disruption of farming calendars, an increase in the likely failure of crops, and severely impact rain-fed farming both in terms of access to reliable precipitation as well as input-based farming, with rain-fed accounting for more than 50% of cultivated land (Mansouri Daneshvar et al., 2019).

As seen in Table 2, for crops such as wheat, rice, and maize, yields have been decreasing due to hotter temperatures and variable precipitation, while adaptation has relied on drought resistant varieties, irrigation and conservation practices (Karimi et al., 2018; Rajabalinejad et al., 2024). Climate variability has implications on crop productivity, water resources and stability in agro-ecosystems, and wheat and barley are losing yields due to heat stress and insufficient soil moisture. Additionally, weed and pest distributions are changing; for example, winter weeds are surviving winters in warmer regions, and C₄ weeds are expected to perform better than

C₃ crops in elevated CO₂ (Peters et al., 2014; Mansouri Daneshvar et al., 2019).

More frequent droughts are leading to depletion of groundwater resources, land degradation and abandonment of farmland in vulnerable provinces such as Sistan and Baluchestan, Khorasan and Isfahan contributing to migration from rural areas along with loss of livelihood (Mansouri Daneshvar et al., 2019).

Urgent adaptation must take place around varieties of crops that are drought resistant, better irrigation practices, conservation practices and climate responsive planting. Long-term resilience will depend on intergraded policies that link climate projections to policies related to land, water and management of agricultural activities. Without acting in a proactive manner temperature will rise, water will become scarcer in newly vulnerable areas and extremes of climate will pose and increased threat to food security and rural development in Iran (Adams et al., 1998; Mansouri Daneshvar et al., 2019; Karimi et al., 2018).

Table 2: Impacts of climate change on agriculture in Iran (Based on Karimi et al., 2018; and Rajabalinejad et al., 2024)

Crop / Sector	Climate Stressor	Region / Study Scope	Projected Impact on Yield / Production	Key Findings & Mechanisms	Adaptation Strategies Identified
Rainfed Wheat	Increased temperature, decreased precipitation	Nationwide	↓ 18% by 2025; ↓ 24% by 2050s	Higher temperatures reduce grain filling period; water stress in critical growth stages.	Adjust planting dates, improve drought-tolerant varieties, expand irrigation.
Irrigated Wheat	Rising temperatures, heat stress	Nationwide	↓ 10–15% under RCP 8.5 by 2050	Heat stress during flowering and grain filling reduces yield. Elevated CO ₂ may partially offset losses.	Use of heat-tolerant cultivars, optimized irrigation scheduling.
Maize	Temperature rise, water scarcity	Khorasan, Fars, Isfahan	↓ 12–20% by 2050	High sensitivity to heat during pollination; reduced water availability in key growing regions.	Shift planting dates, adopt drip irrigation, use hybrid drought-resistant varieties.
Barley	Drought, rising temperatures	Central and Eastern Iran	↓ 15–25% in rainfed systems	Barley is relatively drought-tolerant but yield declines under prolonged drought and heatwaves.	Conservation tillage, improved seed varieties, rainwater harvesting.
Alfalfa	Reduced water availability, heat stress	Nationwide	↓ 8–15% in forage yield	Decline in biomass production due to shortened growing season and reduced water use efficiency.	Adopt deficit irrigation, shift to more resilient forage species.
Rice	Water scarcity, increased evapotranspiration	Northern Iran (Guilan, Mazandaran)	↓ 10–30% due to reduced water allocation	Rice cultivation highly water-intensive; competition with urban and industrial sectors.	Promote alternate wetting and drying (AWD), shift to less water-demanding crops.
Fruits (e.g., Citrus, Dates, Pistachio)	Warmer winters, heatwaves, water stress	Southern & Central Iran (Kerman, Hormozgan)	↓ Yield and quality; ↑ pest/disease incidence	Reduced chilling hours affect flowering; extreme heat damages fruit set.	Net shading, mulching, improved irrigation, shift to tolerant rootstocks.
Vegetables (Greenhouse & Open-field)	Temperature extremes, water scarcity	Nationwide	↓ Productivity in open fields; ↑ energy cost in greenhouses	Heat stress reduces pollination; water shortages limit cultivation area.	Expand greenhouse farming with climate control, use drought-tolerant varieties.
Livestock	Heat stress, reduced forage & water availability	Nationwide (especially arid zones)	↓ Milk production, ↓ animal growth, ↑ mortality	Heat stress reduces feed intake and reproductive performance; pasture degradation.	Improve animal housing, provide shade, develop drought-resilient fodder systems.
Overall Agricultural Productivity	Climate variability, drought frequency	Nationwide	↓ 5–25% across sectors by 2050	Recurrent droughts (e.g., Lake Urmia crisis) reduce cultivated area and increase production risk.	Integrated water management, drought early warning systems, crop diversification.

Effect of Climate Change on Weeds

Changes to Weed Distribution and Composition

Climate change is reshaping weed distribution and community composition through increasing temperatures, altered precipitation regimes, and elevated atmospheric CO₂ (Peters et al., 2014). These changes favor thermophilic and drought-tolerant weed species, promoting northward and upward range expansions of species such as *Abutilon theophrasti* and *Sorghum halepense* (Weber & Gut, 2005; Mozaffari et al., 2022), while enabling invasive species like *Prosopis juliflora* to colonize new areas (Amiri et al., 2022). Consequently, weed communities are increasingly dominated by broadleaf and C₄ grassy species (e.g., *Echinochloa crus-galli* and *Setaria* spp.), (Shafiee et al., 2024). Climate-driven niche shifts, earlier flowering, extended germination

periods, and increased biomass and seed production under elevated CO₂ are expected to enhance weed competitiveness (Broennimann et al., 2007; Mousavi Kouhi & Erfanian, 2020). Iran's complex topography and climatic heterogeneity make its ecosystems particularly sensitive to climate change. Studies from the Central Zagros indicate substantial reductions and altitudinal shifts in suitable habitats of native woody and shrub species. Ensemble modeling of *Amygdalus scoparia* predicted habitat losses of 43–59% by 2050 under RCP4.5 and RCP8.5, with suitability shifting toward higher elevations (Haidarian Aghakhani et al., 2017). Similar trends were reported for *Astragalus verus*, for which 45–90% of current habitats may become unsuitable by 2050–2070, increasing risks of fragmentation and population isolation (Teimoori Asl et al., 2020) (Table 3).

Table 3. Summary of climate change impacts on selected plant species in Iran

Species	Region	Climate Scenarios	Main Impacts	Reference
<i>Amygdalus scoparia</i>	Central Zagros	RCP4.5, RCP8.5 (2050)	43–59% habitat loss; altitudinal shift	Haidarian Aghakhani et al., 2017
<i>Astragalus verus</i>	Central Zagros	RCP2.6–8.5 (2050–2070)	Up to 89.9% habitat loss; upward migration	Teimoori Asl et al., 2020
<i>Artemisia aucheri</i>	Alborz (Mazandaran)	RCP4.5, RCP8.5	Habitat redistribution; decline under severe warming	Ghelichnia, 2025
<i>Bromus tomentellus</i>	Central Zagros	RCP4.5, RCP8.5 (2050)	75–100% reduction; elevation shift	Fakhimi & Khodaghali, 2023
<i>Artemisia sieberi</i>	Central Iran	RCP2.6, RCP8.5	Habitat decline; desertification risk	Amiri et al., 2019
<i>Dodartia orientalis</i>	Iran & global	Future climate	Expansion to higher latitudes	Shadloo et al., 2020
<i>Anchusa italica</i>	Khorasan Razavi province	RCP 8.5	reduce a little less than 40% of suitable habitats	Farzadmehr and Sangoony, 2020

Climate-induced redistribution has also been documented in the Alborz rangelands. Moderate warming may increase high-altitude suitability for *Artemisia aucheri*, whereas severe warming reduces optimal habitats across Mazandaran Province (Ghelichnia, 2025). In the Central Zagros, *Bromus tomentellus* is

projected to experience severe habitat contraction (75–100%) under RCP8.5, accompanied by an upward shift of 180–400 m (Fakhimi & Khodaghali, 2023). In steppe and semi-steppe regions, suitable habitats for *Artemisia sieberi* are expected to decline markedly, potentially accelerating

desertification (Amiri et al., 2019), while invasive species such as *Dodartia orientalis* may expand their ranges under future climates (Shadloo et al., 2020) (Table 3). Beyond spatial redistribution, climate change also alters weed population dynamics. Oveisi (2021) showed that increasing temperatures and changing soil moisture regimes generally enhance weed emergence rates, seedling densities, and emergence duration. Final germination is more strongly controlled by stratification temperature, whereas mean germination time is more sensitive to soil moisture, particularly in drought-prone environments. These physiological and phenological responses are likely to further increase weed competitiveness under future climatic conditions. Utilizing modeling on the RCP 8.5 scenario, a study conducted in Khorasan Razavi province predicted the future occurrence of *Anchusa italica* by the year 2080. The authors found that climate change will reduce a little less than 40% of suitable habitats for this invasive species (Farzadmehr and Sangoony, 2020) (Table 3). Overall, evidence from Iran indicates that climate change will drive habitat contraction, altitudinal and latitudinal shifts, and altered population dynamics across diverse plant functional groups. Integrating species distribution models with demographic and phenological approaches is therefore crucial for improving predictions of ecosystem responses and supporting adaptive conservation and land management strategies.

Effects on Weed Growth

Climatic changes will lead to enhanced growth, vigor, and reproduction of many species of weeds; however, species responses vary depending on the species and ecological consideration of (C₃ vs. C₄) photosynthetic types (Ziska, 2003; Ziska et al., 1999; Das et al., 2017). Increased CO₂ levels (550–700 ppm), directly stimulate both biomass, leaf area, and seed production, particularly for C₃ weed species (e.g., *Chenopodium album*, *Amaranthus retroflexus*, and *Portulaca*

oleracea), with biomass increases of 60–80% and doubling of seed production. C₄ weeds will benefit from temperature increases, CO₂ enrichment, moisture, and the combination of the previous reasons, which can lead to larger canopies and therefore increase competition for available light, water and nutrients (Ziska & George, 2004).

Increasing temperatures can stimulate metabolism, leading to faster germination, earlier flowering time of weeds and potentially, the growing season of weeds (Westerman et al., 2012; Peters et al., 2014). Thermophilic species are now reproducing in areas that were once limited by cold. In particular, some of the warmer winters in Iran will significantly decrease the need for vernalization, resulting in reorganization of the life histories of biennials and winter annual weeds. Changes in precipitation, variability, droughts, and more intense weather events will also create new niches for opportunistic weeds. Weeds that tolerate drought such as *Amaranthus palmeri* and *Portulaca oleracea* are favored under drought stress because of their deep root systems, succulent tissues, or CAM-like physiology. In semi-arid regions of Iran, these weeds will replace crops in rain-fed systems more frequently, and erratic rainfall patterns may increase germination events and complicate management. High phenotypic plasticity, fast growth rates, high fecundity, and broad tolerances allows weeds to outcompete crops in the face of climate change (Patterson, 1995).

Effects of Weed-Crop Competition

Climate change is modifying the competitive relationship between crops and weeds, typically promoting weeds due to higher atmospheric CO₂, heat, and drought (e.g., Alberto et al., 1996; Ziska et al., 2010; Ziska, 2011). The elevated CO₂ can promote photosynthesis, biomass, total leaf area and seed production in C₃ weeds, including *Chenopodium album*, *Amaranthus retroflexus* and *Portulaca oleracea*, but also has advantages for C₄ weeds

(*Echinochloa glabrescens* and *Setaria viridis*) at higher temperatures ($>30^{\circ}\text{C}$) (Ziska, 2003; Das et al. 2017). In Iran, research analysis suggests CO_2 enrichment reduces crop productivity for both C_3 and C_4 crops when

exposed to drought stress, yet crop fertility and yield varied based on species at each moisture level (Miri & Rastegar, 2012; Miri, 2013; Oraki et al., 2016; Anvarkhah et al., 2011) (Table 4).

Table 4. Effects of different CO_2 concentrations on crop–weed competition

CO_2 concentration (ppm)	Crop(s)	Weed(s)	Main Results	Reference
350 vs. 700	Soybean (C_3), Millet (C_4)	Redroot pigweed (C_4), Lambsquarter (C_3)	CO_2 enrichment increased chlorophyll index more in C_3 (20%) than C_4 (12%). Biomass (root, leaf, stem) increased more in C_3 than C_4 . Shoot dry weight of C_4 decreased under competition with C_3 . Soybean PRY increased; millet PRY decreased under elevated CO_2 .	Miri & Rastegar, 2012
400 vs. 700 with drought and control irrigation	Corn (C_4), Wheat (C_3), Sunflower (C_3), Millet (C_4)	Redroot Pigweed (C_4), Lambsquarter (C_3), Wild oat (C_3), Johnson grass (C_4)	Elevated CO_2 increased growth in wheat, sunflower, lambsquarter, wild oat; no significant effect on corn, millet, pigweed, Johnson grass. Drought reduced biomass strongly, but elevated CO_2 alleviated effects. Competitiveness of C_3 weeds increased against corn.	Miri, 2013
400, 700, 1000	Wheat (C_3)	Wild oat (C_3)	Higher CO_2 increased wheat yield and components. Weed density reduced yield across all CO_2 levels. Yield loss due to 100 wild oat plants m^{-2} was 76.5%, 78.3%, 88.8% at 400, 700, 1000 ppm CO_2 respectively.	Oraki et al., 2016
360 vs. 700	Millet (C_4), Soybean (C_3)	Redroot Pigweed (C_4), Lambsquarter (C_3)	Elevated CO_2 increased leaf area and root dry weight of millet, decreased in soybean, pigweed, lambsquarter. Root length increased in millet but decreased in others. Chlorophyll increased in lambsquarter, decreased in pigweed, millet, soybean.	Anvarkhah et al., 2011

Effect of Climate Change on Weed Management Strategies

Climate change is making traditional weed control less effective and thus requires adaptive, integrated, and predictive strategies. Important climatic factors change weed physiology, phenology, distribution, and competitiveness (i.e. ability to compete for resources), which undermine mechanical, chemical, and biological control practices include elevated CO_2 , temperature, precipitation, and extreme weather (Anwar et al., 2021; Ziska, 2020).

Chemical Control

Herbicides specifically are still a staple of modern agriculture, but the efficacy of herbicides is becoming more compromised with climate change. The factors, elevated CO_2 and higher temperatures, affects uptake, translocation, persistence, and mode of action

which negatively impacts efficacy and overall yield. Under CO_2 enrichment (550-700 ppm by mid-century), weed growth will likely be accelerated, increasing biomass and diluting herbicide concentration in tissue (Ziska, 2016; Ziska et al., 2004; Archambault et al., 2001). For example, Bitarafan et al. (2025) reported that elevated CO_2 and temperature caused an increase in ED_{50} for pyroxsulam applied to *Avena fatua*, *Echinochloa crus-galli*, and *Brassica napus*, due to a dilution effect, spraying herbicides more effectively (1.3–2.1) times (Table 5).

The response of herbicides can vary depending on species and chemical. The efficacy of glyphosate decreases in both C_3 (*Chenopodium album*) and C_4 weeds (*Chloris gayana* and *Paspalum dilatatum*) due to a higher vegetation biomass and leaf area (Manea et al., 2011; Ziska et al., 1999). In comparison, the efficacy of 2,4-D can increase by 26.9%, while

the efficacy of clopyralid decreases by 8.9% (Archambault et al., 2001), demonstrating the need to consider chemical variability in herbicide efficacy. In addition to CO₂, both hot and cold temperatures will affect herbicide activity. Hot temperatures increase plant metabolism, which will increase detoxification of the herbicide (cytochrome P450) and subsequently reduce the efficacy of herbicides (Matzrafi et al., 2016). Increased temperature can also increase the volatility of some herbicides (triallate losses of 14–60% from 5°C to 25°C; Atienza et al., 2001), can increase the drying time for droplets, and will increase the degradation of mesotrione and sulfonylurea herbicides (Godar et al., 2015; Olson et al., 2000). The low temperatures slow down plant metabolism and the absorption and distribution of systemic herbicides like glyphosate and imazethapyr. This slows down the action of herbicides, and in some cases can render a selective herbicide non-selective, which would lead to increased crop damage (Madafiglio et al., 2000). Freezing temperatures also reduce the effectiveness of mesosulfuron-methyl + iodosulfuron-methyl-sodium on *Avena sterilis* and *Rapistrum rugosum*, especially if applied in anticipation of frost; GR₅₀ values tend to increase (Hasanfard et al., 2022, 2023) (Table 5). For most herbicides, such as glyphosate and imazethapyr, efficacy is generally best between 25–35°C; and, diurnal timing can affect efficacy (Stoppes et al., 2013; Johnson et al., 2002).

Drought caused by climate change can reduce the efficacy of pre- and post-emergence herbicides by limiting absorption, translocation, and activity in weeds, posing challenges for chemical weed control (Alizade et al., 2020 and 2021; Abdolahi Norouzi et al., 2024) (Table 5). Hammami & Mirzaei Nasab (2025) showed that increasing drought stress significantly reduced the efficacy of the clethodim in controlling littleseed canarygrass (*Phalaris minor*), as indicated by markedly higher ED₉₀ values for shoot and root fresh and dry weights under 50% field capacity compared with well-watered conditions. In similar study,

under reduced moisture regimes the efficacy of the herbicide imazethapyr declined markedly, such that even the full recommended dose failed to adequately control weeds compared with well-watered conditions (Rastgordani et al., 2023) (Table 5). Climate change, especially due to warmer temperatures and changes in soil conditions, has been demonstrated to reduce the longevity and effectiveness of soil-applied herbicides profoundly. For example, Bailey (2003) investigated the effects of climate change on isoproturon persistence in UK soils, using the increased soil temperatures due to climate change, and demonstrated loss of persistence of isoproturon applied in the autumn. In fact, between the early to late 1990s when soil temperatures increased, the residues of isoproturon decreased around 30 days faster, which resulted in approximately 25% less weed control. This study demonstrates that projected temperature warming in the future will also affect the persistence and effectiveness of soil-applied herbicides. Dust can create a mechanical barrier that will limit herbicide uptake and efficacy (glyphosate, paraquat, 2,4-D+MCPA) and can potentially require up to a 1.9–2.6× higher herbicide application rate, with data being herbicide-specific (Asadi-Sabzi et al., 2020; Sharifi Kalyani et al., 2024) (Table 5).

High relative humidity increases foliar uptake, while low relative humidity increases evaporation rates and, subsequently, decreases foliar efficacy in herbicide efficacy (Anderson et al., 1993; Kudsk et al., 1990). Wind can reduce deposition of herbicides either through drift, or increase herbicide penetration if the falsity is eaten through the uneven leaf surface. Rain can wash off foliar-active herbicides; heavy rainfall reduces residual efficacy of pre-emergence herbicides, while light dew may improve residual pre-emergent performance (Inoue et al., 2010). Solar radiation and UV-B radiation increases wax deposition on plant surfaces, which reduces absorption of herbicide and photodegrades herbicides faster, reducing the herbicide activity duration and herbicide efficacy (Katagi, 2004).

Table 5: Effects of different environmental factors on herbicide performance in different weed species.

Herbicide	Factor	Weed Species	Impacts	Reference(s)
Sulfosulfuron	Drought	<i>Hordeum spontaneum</i>	Efficacy was not significantly affected by drought stress; no change in ED ₉₀ .	Alizade et al. (2020 and 2021)
Sulfosulfuron		<i>Sinapis arvensis</i>	Efficacy decreased under drought; ED ₉₀ increased from 1	
Mesosulfuron-methyl + iodosulfuron-methyl-sodium		<i>Avena sterilis</i> subsp. <i>ludoviciana</i>	Efficacy reduced under drought with a 1.5-fold increase in ED ₅₀ . Linked to reduced stomatal conductance and photosynthesis. Low doses caused hormesis.	
Clodinafop-propargyl		<i>Avena sterilis</i> subsp. <i>ludoviciana</i>	Efficacy reduced under drought stress	
Sulfosulfuron + metsulfuron-methyl		<i>Hordeum spontaneum</i>	No significant reduction in efficacy	
imazethapyr		Total Weed Species	Efficacy reduced under drought stress	Rastgordani et. al. (2023)
Clethodim		<i>Phalaris minor</i>	Efficacy reduced under drought (50% field capacity). ED ₉₀ and ED ₅₀ for shoot and root fresh/dry weight increased by 17–86%. Drought reduces herbicide absorption and translocation due to thicker cuticle and reduced vascular flow.	Hammami & Mirzaei Nasab (2025)
Sulfosulfuron		<i>Hordeum spontaneum</i>	Reduced herbicide efficacy; ED ₉₀ increased from 27 g ai ha ⁻¹ (irrigated) to 63,248 g ai ha ⁻¹ (water-stressed).	Abdollahi Norouzi et. al. (2024)
		<i>Sinapis arvensis</i>	Reduced herbicide efficacy; ED ₉₀ increased from 1,022.4 g ai ha ⁻¹ (irrigated) to 1,862.9 g ai ha ⁻¹ (water-stressed).	
Pyroxsulam	Elevated CO ₂ and Temperature	<i>Avena fatua</i> , <i>Echinochloa crus-galli</i> , <i>Brassica napus</i>	Under elevated CO ₂ (800 ppm) and higher temperature, the efficacy of pyroxsulam was reduced for all three species. The ED ₅₀ increased by 1.3 to 2.1 times compared to ambient conditions. This is attributed to faster growth, increased biomass (dilution effect), and altered plant physiology under climate change conditions.	Bitarafan et al. (2025)
Glyphosate	Airborne Dust	<i>Hordeum spontaneum</i> and <i>Sinapis arvensis</i>	Efficacy significantly reduced by dust; herbicide dose needed to be increased 1.9–2.6 times for effective control. Dust acts as a physical/chemical barrier to foliar absorption.	Asadi-Sabzi et al. (2020)
Paraquat		<i>Hordeum spontaneum</i> and <i>Sinapis arvensis</i>	Efficacy significantly reduced by dust deposition. Requires higher doses or adjuvants for effective control under dusty conditions.	
2,4-D + MCPA		<i>Hordeum spontaneum</i> and <i>Sinapis arvensis</i>	Efficacy significantly reduced by dust. Performance dropped due to limited penetration through dust-coated leaf surfaces.	
Sulfosulfuron		<i>Hordeum spontaneum</i>	No significant reduction in efficacy under dust.	
Tribenuron-methyl		<i>Amaranthus retroflexus</i>	Enhanced efficacy in the presence of dust; achieved 95.8% control. Dust may have contributed to stress increasing herbicide susceptibility.	Sharifi Kalyani et al. (2024)
Aminopyralid + florasulam		<i>Amaranthus retroflexus</i>	Enhanced efficacy with dust; 95.7% control. Dust-induced stress may have amplified herbicide action.	
Foramsulfuron + iodosulfuron + thiencazone		<i>Amaranthus retroflexus</i>	Enhanced efficacy under dust; 97.8% control. Dust may have acted synergistically or increased plant stress.	
2,4-D + MCPA		<i>Amaranthus retroflexus</i>	Reduced efficacy in the presence of dust; performance negatively affected.	
Bentazon (BNT)		<i>Amaranthus retroflexus</i>	Significantly reduced efficacy under dust; caused only 28% height reduction and 29% biomass decrease compared to non-dust conditions.	
Acetochlor (ACR)	<i>Amaranthus retroflexus</i>	No significant difference in efficacy under dust; performed similarly in both conditions.		
Mesosulfuron-methyl + iodosulfuron-methyl-sodium + mefenpyr-diethyl	Freezing Stress	<i>Avena sterilis</i> subsp. <i>ludoviciana</i> and <i>Rapistrum rugosum</i>	Efficacy reduced under freezing" especially "before spraying (FBS). Survival rates increased by 47–58%. LD ₅₀ /GR ₅₀ : NF < FAS < FBS. Selectivity in wheat severely compromised.	Hasanfard et al. (2022)
Sulfosulfuron + metsulfuron-methyl		<i>Hordeum spontaneum</i> and <i>Sinapis arvensis</i>	Efficacy significantly reduced under freezing" especially before spray. ED ₅₀ for " <i>H. spontaneum</i> " increased 11.3-fold under FBS. Freezing reduced stomatal conductance and photosynthesis limiting herbicide uptake."	Hasanfard et al. (2023)
Clodinafop-propargyl		<i>Avena sterilis</i> subsp. <i>ludoviciana</i>	Efficacy reduced under freezing stress. Relative potency < 1 indicates lower efficacy. Reduction was 33% in FAS and 1% in FBS treatments.	
2,4-D + MCPA		<i>Avena sterilis</i> subsp. <i>ludoviciana</i>	Efficacy reduced under freezing stress. Relative potency < 1. Reduction was 38% in FBS and 8% in FAS, indicating pre-spray freezing has a greater negative impact.	

Climate Change and Herbicide Resistance

Resistance to herbicides is a significant issue in contemporary agricultural systems. Climate change has proven to alter weed physiology and promotes the evolution and dispersal of resistant biotypes. An increase in CO₂, temperature, drought, and other forms of stress apply more selection pressure onto weeds, resulting in increased tolerance, detoxification and survival during exposure to herbicides (Anwar et al., 2021). Increased CO₂: In general, an increase in weed biomass and growth will result in a dilution of herbicide concentration (the "dilution effect"), therefore aggravating resistance (for example, *Cirsium arvense* and *Elytrigia repens*) (Ziska et al., 2004). Increased CO₂ has been shown to upregulate the expression of detoxification enzymes, such as cytochrome P₄₅₀ that mimic or enhance genetic resistance to herbicides. Reports show that C₃ and C₄ weed species (e.g., *Chenopodium album* and *Amaranthus retroflexus* respectively) can also demonstrate increased tolerances to glyphosate (Ziska et al., 1999).

Climate stress: drought, heat or nutrient deficient situations select for 'super individuals' that possess traits to reduce herbicide uptake, these situations aid in promoting resistant phenotypes (Matzrafi et al., 2016).

Accelerated Life Cycles: Warmer temperatures and prolonged seasons enable several generations and enhance mutation rates, which accelerate the evolution of resistance in short-lived, variable species (*Amaranthus palmeri*, *Lolium rigidum*) (Anwar et al., 2021).

Herbicide Persistence and Sub-Lethal Exposure:

Increasing temperatures and irregular rainfall can decrease herbicide residual activity and promote multiple sub-lethal exposures, which increases the chances of resistance developing (Anwar et al., 2021).

Indirect Effects from Crop-Weed Competition:

Crop stress reduces crop competitive ability, which favors weed dominance, thus increasing herbicide applications and accelerating the selection of herbicide-resistant weed populations (Anwar et al., 2021).

Mechanical Control

Mechanical weed control remains an essential tool in integrated weed management (IWM), especially in organic production and areas where the use of chemicals is limited by herbicide resistance and/or environmental concerns. However, climate change is increasingly compromising the effectiveness of mechanical means of weed control by changing the morphology and phenology of weeds, and changing soil physical properties. Key driving forces include increasing atmospheric CO₂, changing temperature regimes, and changing precipitation patterns, which can lead to less successful weed control, more operationally expensive, and to involuntary facilitation of weed dispersal.

Increased Root:Shoot Ratio and Generally Higher Belowground Biomass Production:

The most noteworthy physiological response of perennial weeds to high CO₂ levels is an alteration in biomass distribution to underground plant parts. Increased CO₂ results in enhanced carbon fixation (i.e., photosynthesis), resulting in increased biomass allocation to root, rhizome, stolon, and tuber growth, which are of vital importance in vegetative propagation and survival (Ziska, 1997). Increased biomass allocation would lead to an increased root:shoot ratio and thus increase the resilience of perennial weeds to mechanical disturbance. Canada thistle (*Cirsium arvense*), Johnson grass (*Sorghum halepense*), quackgrass (*Elytrigia repens*), skeletonweed (*Chondrilla juncea*), and

silverleaf nightshade (*Solanum elaeagnifolium*) are capable of responding dramatically to increased CO₂ with significant increases in their rhizome and root biomass, thus increasing their capacity for regeneration (Ziska et al., 2004). This ultimately means that shallow tillage or disking will not remove the full complement of underground propagules, and fragmenting propagules will regenerate after tillage. Moreover, and most importantly, mechanical tillage may actually promote weed populations in a high CO₂ environment. Tillage operations leading to fragmentation of rhizomes or roots may lead to increased weed infestations by promoting vegetative, asexual reproduction (Ziska, 2020). Consequently, mechanical control will shift from a method of suppression to a mechanism for weed dispersal, especially for those species that propagate vegetatively.

Altered Patterns of Emergence and Timing:

Climate change has altered weed emergence timing and synchrony patterns, leading to considerable implications for the timing of mechanical operations. Warmer springs and winters are associated with earlier and extended emergence windows in the form of asynchronous emergences and multiple flushes within the same growing season. These altered emergence patterns mean that different kinds of welfare practices (ex: pre-plant tillage, tack methods, and inter-row cultivation) will be less effective; these practices are designed to target a single and reliable emergence peak. In terms of implementing delayed or multiple mechanical operations, fuel consumption, labor hours, and soil compaction are directly affected. Moreover, the risk of increased soil erosion associated with extreme events is heightened. Changing patterns of rain, which include droughts and torrential storms, are also likely to add complexity to field operations with unpredictable soil windows of workability

causing challenges with implementing timely weed intervention (Ziska, 2020).

Soil Moisture Extremes and Tillage Efficiency:

Changes to climate such as changes in precipitation and evapotranspiration directly affect soil physical conditions, affecting the performance of mechanical tools. For instance, dry soils become hard which decrease the penetration depth of tillage tools, compromising their ability to uproot weed species. Very wet soil caused by heavy rain or precipitation delays access to fields for operation and damages soil structure over time during tillage (e.g., compaction, smearing). Changes in soil moisture abrades mechanical weed control in conservation tillage/no-till systems, which are becoming increasingly favorable for conserving moisture and minimizing erosion. Less disturbance from tillage results in more perennial, rhizomatous, and stress tolerant weed species establishment, which is less reliant on germination from weed seeds and vegetatively spreads. The change in weed species composition towards mechanically resistant weed species may limit the efficacy of mechanical control and reassess long-term tillage plans (Ziska, 2020).

Biological Control

Increasing temperatures along with altered precipitation and elevated levels of CO₂ will disrupt the ecological synchronize (or coordination) between invasive weeds and their biological control agents and could lead to reduced efficacy of these agents. Climate change might shift both weeds and their natural enemies to different geographic ranges, resulting in a mismatch between the distributions of a weed and its biocontrol agents. In addition, unequal ecological responses to climate stressors will elevate physiological and phenological traits of these species, which could modify host specificity

and performance of the agents (Sun et al., 2020). Biological control is reliant on host-specific agents, such as insects, mites, or fungi, which are extremely sensitive to environmental factors (Augustinus et al., 2020). Climate change may disrupt the delicately balanced ecological relationship associated with biological control.

Mismatch in Phenology Between Weeds and Agents:

Climate change will alter the phenology (timing of life histories) of both weeds and their biological control agents. In the case of weeds, if a weed emerges earlier as a result of warming, but the control agent (e.g. herbivorous beetle) does not exercise its activity until a particular season or lifecycle cue occurs, then a temporal mismatch will exist, subsequently reducing control effectiveness (Sun et al., 2020). For example, if *Ambrosia artemisiifolia* (ragweed) flowers earlier (due to elevated CO₂ and warming) than its natural enemies, and those enemies do not increase activity, a mismatch occurs (Ziska et al., 2019).

Changes in plant chemistry and herbivore performance:

Increased atmospheric CO₂ levels alter the nutritional quality and secondary metabolite profile of weeds. The resulting increase in the C:N (carbon to nitrogen) ratio negatively affects herbivore nutritional quality from plant tissue. Changes in alkaloids, tannins, or terpenes, can deter herbivore feeding or even reduce herbivore growth and reproduction (Bidart-Bouzat et al., 2008; Loladze, 2014). While biocontrol agents may be present, these changes may reduce their effectiveness.

Range shifts of biocontrol agents:

Biological control agents are typically introduced from the native range of the weed and may not adapt to climatic change as quickly

as the weed itself. Invasive weeds may expand their range poleward or climb in elevation, but their herbivore specialist may not keep pace, leading to "enemy-free space" that allows the weed to spread (Bradley et al., 2010). In certain situations, warming may enable non-target or generalist herbivores to invade, thus disrupting existing biological control programs. Case In Point, the leaf beetle *Ophraella communa* was introduced as a biological control agent for *Ambrosia artemisiifolia* and has exhibited high efficacy in Europe and Asia. Yet, under elevated levels of CO₂, ragweed will produce more pollen and develop denser leaf structures, which could lead to overwhelming beetle populations (Ziska et al., 2019). Additionally, changes in temperature and humidity could affect beetle survival, fecundity, and dispersal, thus causing profound alterations to long-term biological control outcomes (Cardarelli et al., 2018).

Predictive modeling approaches, including mechanistic niche models, are necessary for anticipating range shifts of invasive weeds and their biological control agents, and improving the selection of effective agents. In addition, to enhance success in the biological control of invasive species under climate change, there needs to be greater post-release monitoring, consideration of evolutionary adaptation potential, and integration of biological control with complementary management strategies to improve overall resilience (Sun et al., 2020).

Recommendations and Adaptive Weed Management Strategies

Climate change has created complex challenges for weed management. Rising temperatures, altered rainfall patterns, and greater climate variability favor more competitive, herbicide-resistant weed biotypes (Ramesh et al., 2017), intensifying crop competition and reducing herbicide efficacy (Marambe & Wijesundara, 2021). Heat and drought stress further weaken

crops, increasing susceptibility to weed dominance. Shifts in weed phenology, earlier emergence, longer growing seasons, and multiple flushes, complicate timing for chemical and mechanical control, raising the risk of resistance evolution (Anwar et al., 2021). Over-application of herbicides exacerbates resistance, with 16 species $\times$ site-of-action cases reported in Iran affecting key crops such as wheat and maize (Heap, 2025), while repeated applications increase energy use and greenhouse gas emissions (Lu et al., 2022). New invasive weeds further threaten yields, soil health, and biodiversity (Turbelin & Catford, 2021).

Climate change also drives adoption of integrated weed management (IWM). IWM combines chemical, mechanical, cultural, and biological measures adapted to rapidly changing conditions (Davis et al., 2017). Precision agriculture tools, remote sensing, GIS mapping, drones, and GPS-guided herbicide application, reduce chemical use and improve efficiency, while decision-support systems optimize timing based on weather and phenology (Cheema et al., 2023). Developing climate-resilient crops with denser canopies, drought tolerance, and competitive ability suppresses weed growth and stabilizes yields (Hafeez et al., 2023). Sustainable practices like crop rotation, cover cropping, and soil health improvement reduce weed seed banks and enhance agroecosystem resilience, as shown in chickpea and wheat systems in Iran (Nosratti et al., 2020). Farmer education and supportive policies are essential. Training programs, extension services, and governmental incentives promote adoption of climate-smart, low-chemical strategies (Gemtou et al., 2024). Policies must support research, seed development, precision technologies, integrated practices, and sustainable herbicide regulation to align with climate realities. Collaboration among researchers, farmers,

extension agents, and policymakers is crucial for adaptive, sustainable weed management (Marambe & Wijesundara, 2021).

To tackle the multifaceted problems from climate change related to weed dynamics in Iran, it is necessary to use holistic, science-based adaptive management approaches (Table 6). These should be multi-dimensional, integrating approaches simultaneously to support sustainable agriculture, crop yield, and ecosystem health under changing conditions.

Integrated Weed Management (IWM) Focus:

The approach will emphasize the use of Integrated Weed Management (IWM), which utilizes chemical, cultural, mechanical, and biological options in tandem to reduce herbicide use and mitigate resistance. Successful trials in Iranian wheat and olive orchards have shown that IWM types not only achieve better weed control compared to single options, they also achieve better energy efficiency and lower greenhouse gas emissions (Mohammadi et al., 2025). Iranian farmers' awareness and acceptance of implementing IWM depends on factors such as total income and crop type, and extension services should utilize these factors to promote IWM and increase likelihood of acceptance.

Crop Varieties Adapted for Climate:

It is vital to create and distribute crop varieties that are robust competitors against weeds and tolerant to key abiotic stresses, such as drought and heat. Advanced crop varieties that show good competitive traits in the form of canopy cover can suppress weeds from emerging and establishing; both barley and chickpea breeding programs in Iran have provided supporting evidence of this. We need more research collaboratively to develop new crop varieties that are adapted for competitive traits and face climate stresses.

Table 6. Emerging opportunities and adaptive weed management strategies under climate change (Modified from [Malhi et al., 2021](#)).

Strategy	Description	Key Benefits
Integrated Weed Management (IWM)	A holistic approach combining chemical, mechanical, cultural, and biological control methods to reduce reliance on herbicides.	Slows herbicide resistance development, improves long-term sustainability, and reduces environmental impact.
Precision Agriculture & Real-Time Monitoring	Use of drones (UAVs), remote sensing, GIS-based mapping, and GPS-guided sprayers for site-specific weed detection and control.	Reduces herbicide use by 30–50%, lowers costs, and minimizes non-target effects.
Decision Support Systems (DSS)	Tools integrating weather forecasts, phenological models, and crop-weed competition simulations to optimize timing of control measures.	Enhances decision-making accuracy under variable climate conditions.
Climate-Resilient Crop Varieties	Breeding and deploying crop cultivars with dense canopy cover, early vigor, and competitive ability against weeds under abiotic stress.	Suppresses weed emergence through shading and resource competition; maintains yield stability.
Crop Rotation and Diversification	Rotating crops with different life cycles and growth patterns to disrupt weed seed banks and reduce monoculture-driven weed adaptation.	Breaks weed life cycles, reduces dependency on herbicides, and improves soil health.
Cover Cropping and Conservation Tillage	Using cover crops (e.g., barley, vetch) and minimum tillage to provide ground cover and suppress weed germination.	Reduces soil erosion, enhances organic matter, and physically inhibits weed establishment.
Agroecological Practices	Utilizing allelopathic crop residues, intercropping, and agroforestry to naturally suppress weeds.	Promotes ecological balance and reduces chemical inputs.
Farmer Education and Extension Programs	Training farmers on herbicide resistance, IWM, and climate-smart technologies to improve adoption of sustainable practices.	Increases awareness and capacity for adaptive management at the farm level.
Policy and Institutional Support	Government incentives for precision tools, sustainable herbicide registration, research funding, and extension services.	Enables large-scale adoption of innovative weed management systems.
Research and Monitoring Networks	Long-term monitoring of weed population shifts, resistance trends, and climate impacts using predictive modeling.	Provides early warning and informs adaptive strategies under future scenarios.

Precision Agriculture and Real-Time Monitoring:

Precision agriculture methods allow for precise, localized and technology-based considerations of weed management. The precision agriculture method uses remote sensing, UAV (drone) images, multispectral and hyperspectral technology and precision agriculture with GIS mapping to able to detect weed infestations, record variable-rate herbicide applications in place of a full-rate field application. The technology and precision agriculture lessen overall herbicide inputs, reduce inputs costs,

and lessen off-target pesticide movement to water and soil. Decision support models can also provide up-to-date readings based on weather forecast information and other data (phenology records and growth simulation models) to help in decision making of herbicide application in the best timing and most effective control under ever changing climates.

Crop Rotation, Cover Crops, and Soil Health Management:

When cropping systems are diversified using crop rotation, cover crops, and conservation tillage, the weed seed bank is reduced, weed life

cycle interruptions occur, and soil structure and soil fertility improve. These ecological principles reduce environmental footprints and improve agroecosystem resilience to climate stresses, including in chickpea and wheat production systems in Iran.

Farmer Training and Policy Support:

Comprehensive farmer education and capacity building is integral to the scale adoption of climate-smart weed management practices. Training modules must emphasize integrated approaches to climate-smart weed management, resistance management, technology, and conservation practices. Governmental extension programs and non-governmental organizations must pool resources to improve the knowledge transfer capabilities and strengthen farmer access to inputs and technologies. Long-term weed management sustainability relies on policy supports to promote climate-smart sustainable weed control innovations by incentivizing reduced reliance on chemicals, supporting precision agriculture to improve efficiencies in farming inputs and practices, or expanding product registrations for herbicides with unique modes of action for crop production.

Research and Monitoring Improvement:

Continuous research is essential for monitoring shifts in weed populations, resistance trends, and climate effects. Improved data collection at the regional level and predictive modeling of weed-crop interactions within future climate parameters supports promptly adaptive management. Collaborative partnerships between universities, agricultural research centers, and policymakers build capacity for innovation and reduce knowledge gaps contributing to the sustainable management of weeds.

Conclusion

Visible shifts in climate are occurring in Iran's arid and semiarid regions, demonstrating historical shifts including a projected increase in mean annual temperature of 2.6 °C, and a

projected reduction of precipitation of up to 35% as well as inducing increases in the incidence of extreme events (e.g., heatwaves, droughts and dust storms). These climatic changes favor invasive, thermophilic, and drought-tolerant weed species that are invading and establishing within these extreme ecosystems. Climatic changes not only allow invading disruptive weeds to continue their northward or upward distribution, but they give weeds a relative advantage over cultivated crops for a variety of phenological, physiological and ecological reasons such as increased growth at ambient high CO₂ temperature, changes in phenology, and through imposing rapid evolutionary mechanisms such as herbicide resistance. The invasive weeds further minimize yield of staple crops (e.g., 10-30% loss of major crops like maize, rice, and wheat) and complicate their management. Herbicides are rendered ineffective due to physiological constraints and ecological interactions, mechanical methods hazard transmitting perennial weeds; and biological control agents become less effective if the agent/host is not in synchrony. In addition to indirect effects such as adaptive modifications to farming systems and soil degradation, which undoubtedly pose significant risks to national food security, human and economic health, and environmental integrity, they also present potential opportunities for innovation and resilience. Since risk often carries the possibility of innovation, a shift from reactive to proactive integrated weed management (IWM) is imperative. IWM should be combined with appropriate chemical, mechanical, cultural, and biological approaches, and further strengthened by emerging technology-supported decision support systems, remote sensing techniques, and precision agriculture to optimize the timing and efficiency of inputs. Together, breeding climate resilient crop cultivars with better competitive traits, diversifying cropped rotations with cover crops (e.g., barley and vetch), and building soil health via reduced tillage conservation systems will

serve to diminish weed pressures and abiotic stressors such as moisture stress while returning carbon to soils. Farmer education and outreach programming also needs to be increased to help stakeholders make sense of resistance risk, and implement sustainable practices, and policies must incentivize reduced input technologies, fund research into modelling and predictions, and hopefully provide access to new/other herbicide modes of action for farmers.

In a future driven by the realities of climate change; ongoing collaboration and exchange amongst researchers, policy makers, extension services and farmers will be required to monitor shifting weed populations, model future scenarios using species distribution models and adjust as needed. Recognizing the reality of

agronomic decisions within limits of ecology and focusing on the long-term aspects of sustainability as opposed to the short-term surprises of reactivity, and with Iran's location to take advantage of both global supply chains and local agriculture, productivity can be sustained, as well as, achieving just food systems for generations to come by facing the reality of climate change. Sustainable management of vulnerabilities associated with weeds using integrated climate-smart solutions will enhance local resilience while simultaneously contributing to the community's capacity to help mitigate the agronomic impact of anthropogenic climate change.

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