

Herbicide resistance: Implications of climate change on the susceptibility of weeds to herbicides – A review

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SUMMARY

Climate change is a major issue in agricultural sustainability posing severe problems that threaten global food security. Conventional farming often utilizes herbicides to control weeds in most management strategies. In recent times, transformations in weeds due to shifts in climatic conditions across the globe are making management strategies in many ecosystems more complex. Climate variables including high carbon dioxide concentrations, increased temperature levels and altered moisture conditions affect many plants physiology. In weed species, a change in climate conditions can impact growth of weeds and the effectiveness of herbicides used in controlling the weeds. Therefore, there is the need for changes to be made with production practices to reduce emissions and to adapt to a changing climate in agriculture to limit the negative impact of weeds. The aim of this perspective is to deliver insights on herbicide application, describe the effects of climate on weed biology and development, and highlight the necessity to synthesize this information for establishing a long-term framework for sustainable weed management.

Keywords: weed management; herbicide resistance; climate change; herbicide efficacy; carbon dioxide

INTRODUCTION

Evolutional change is a natural phenomenon that ensures continuity of living organisms and has been occurring for ages. Long-term shifts in environmental factors such as weather patterns, precipitation and temperature have influenced the evolution of many organisms since the history of earth (Erwin, 2009; Hoffmann & Sgrò, 2011; Jugulam et al., 2018). However, anthropogenic activities, particularly the combustion of fossil fuels (such as oil, gas, and coal) in the past centuries have become the main drivers of climate change (Reddy, 2015). Greenhouse gases, including carbon dioxide (CO₂), methane, nitrous oxide, and fluorinated gases generated by human activities rose by 44 percent between 1990 and 2015. During this time, CO₂ emissions, which represent approximately three-fourths of total emissions, grew by 50 percent (IPCC, 2021; US EPA, 2015). Expected patterns of future climate change is a prediction of warming over lands, increase in precipitation in the tropics, decrease in precipitation sub-tropical areas and likely expansion of deserts (Ahmed et al., 2019; Le Houérou, 1996; Varghese, 2023). All these weather extremes are expected to have a direct impact on plant life, agriculture and global food security (Jugulam et al., 2018; Parmesan & Yohe, 2003; Varanasi et al., 2016).

Weed management strategies need to be adapted to current climatic conditions in order to ensure optimum results. Weeds are complex in nature, they are highly adaptable to multiple stressors including high temperatures, increased CO₂, waterlogging and drought (Chen et al., 2020). The negative impacts of weeds include yield losses due to weed competition, interference with harvest operations, production of

toxic substances and serving as hosts for pests and plant pathogens (Varanasi et al., 2016). Over the years, climate change has induced transformations in weeds in several ecosystems across the globe. Weeds are expected to exhibit greater resilience and adaptability due to the presence of a diverse genetic pool and their greater physiological plasticity (Peters et al., 2014; Varanasi et al., 2016). This review highlights the effects of climate change on weed development, specifically examining how climate factors influence the physiological mechanisms that contribute to herbicide tolerance in weeds.

Herbicide use

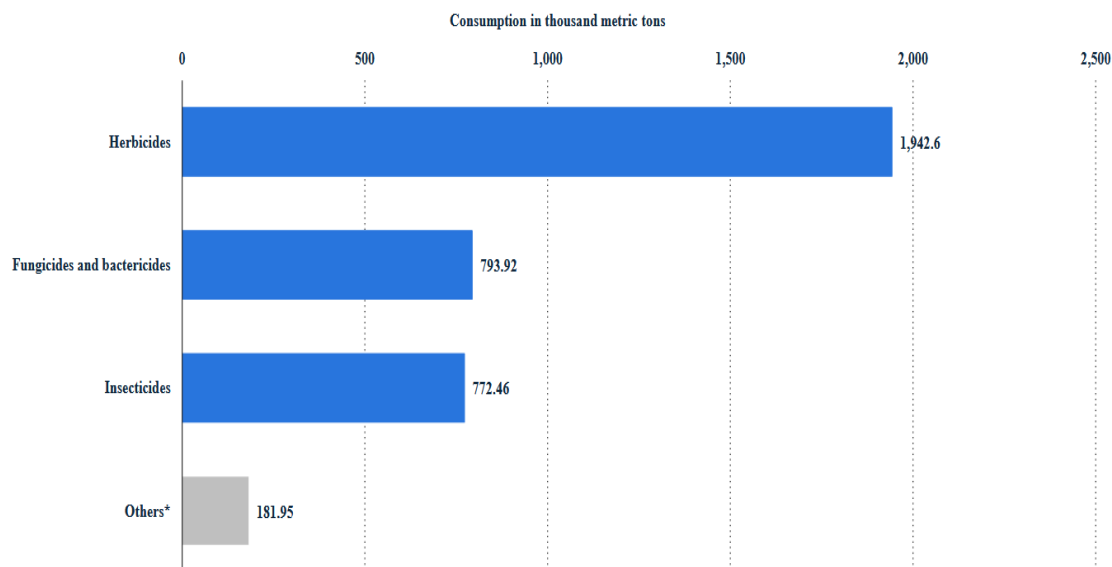
Agricultural pests including insects, mites, pathogens, rodents and weeds have plagued agricultural production since the beginning. These pests adversely affect production yields if not managed properly (Sawicka & Egbuna, 2020; Varanasi et al., 2016). Several pest management strategies have been employed in managing these pests ranging from mechanical, cultural, biological and chemical methods. Chemical control of weeds utilizing herbicides has been extensively used globally in many management strategies by offering a less labour intensive, cost effective, faster approach and greater efficacy in controlling weeds (Jugulam et al., 2018; McErlich & Boydston, 2014). Since the introduction of the synthetic herbicide technology in the 1940s with the introduction of 2,4-Dichlorophenoxyacetic acid (2,4-D), chemical weed management has provided a major technological tool to minimize the impact of agricultural weeds on production (Green, 2014; Ofosu et al., 2023). A report from the Food and Agriculture Organization of the United Nations (FAO) in 2024 indicated that global

agricultural pesticide consumption in 2022 was 3.69 million metric tons. The report also indicated that herbicide consumption was nearly 1.9 million metric tons, while fungicides and bactericides had a

combined consumption of approximately 793.92 thousand metric tons in 2022 as indicated in *Figure 1* (FAO, 2024).

Figure 1. Agricultural consumption of pesticides worldwide in 2022, by type (in 1,000 metric tons)

Data Source: FAOSTAT (2024)



Industrial agriculture has depended on herbicides for food and animal feed production, particularly following the introduction of genetically modified crops that are tolerant to herbicides (Gianessi, 2013; Norsworthy et al., 2012; Patel, 2013; Pingali, 2012). The heavy reliance on herbicides can be explained by their efficiency, cost-effectiveness and simplicity as a means of managing weeds in numerous production systems globally (Monteiro & Santos, 2022; Riemens et al., 2022). Also, herbicide use is expected to increase in developing countries as they seek to significantly increase crop yield (Penna & Lema, 2003). Nonetheless, although herbicides have greatly aided production by offering a reliable, effective, swift, and cost-efficient means of managing weeds, the emergence of herbicide resistance in various weed species is raising international concerns (Clements & Jones, 2021; Heap, 2025). Since the initial report of common groundsel (*Senecio vulgaris*) developing resistance to triazine herbicides, specifically simazine and atrazine, occurred in 1968 (Shaner, 1995), there have been several other cases recorded. Glyphosate

resistant horseweed (*Conyza canadensis*) populations were reported in 2000 in Delaware, United States of America (USA) in a soybean cultivated field (González-Torralva et al., 2012). In Hungary, certain weeds including common ragweed (*Ambrosia artemisiifolia*), cocklebur (*Xanthium italicum*), green amaranth (*Amaranthus powellii*), and Johnsongrass (*Sorghum halapense*) have been observed to have acquired resistance to several acetolactate synthase (ALS) inhibitors (Szabó et al., 2018; Kazinczi & Torma, 2016). The International Herbicide-Resistant Weed Database (2025) shows that herbicide-resistant weeds have been reported in 102 crops across 75 countries. Presently, there are 537 distinct cases (species x site of action) of herbicide-resistant weeds worldwide, comprising 273 species (156 dicotyledons and 117 monocotyledons). Data from the same database reports that weeds have developed resistance to 21 out of the 31 recognized herbicide sites of action and to 168 different herbicide types as indicated in *Table 1*.

Table 1. Number of herbicide-resistant weeds by site of action

Data Source: WeedScience.org (Heap, 2025)

HRAC Group	Site of Action	Dicotyledons	Monocotyledons	Total
2	Inhibition of Acetolactate Synthase	108	68	176
5	PSII inhibitors - Serine 264 Binders	53	34	87
9	Inhibition of Enolpyruvyl Shikimate Phosphate Synthase	29	33	62
1	Inhibition of Acetyl CoA Carboxylase	0	52	52
4	Auxin Mimics	35	9	44
22	PS I Electron Diversion	23	10	33
14	Inhibition of Protoporphyrinogen Oxidase	13	4	17
3	Inhibition of Microtubule Assembly	2	10	12
15	Very Long-Chain Fatty Acid Synthesis Inhibitors	2	8	10
34	Inhibition of Lycopene Cyclase	1	5	6
10	Inhibition of Glutamine Synthetase	1	5	6
6	PSII Inhibitors – Histidine 215 Binders	3	2	5
12	Phytoene Desaturase inhibitors	4	1	5
27	Inhibition of Hydroxyphenyl Pyruvate Dioxygenase	4	1	5
29	Inhibition of Cellulose Synthesis	0	4	4
0	Unknown	0	4	4
13	Inhibition of Deoxy-D-Xylulose Phosphate Synthase	0	3	3
0	Antimicrotubule mitotic disruptor	0	3	3
23	Inhibition of Microtubule Organization	0	1	1
0	Nucleic Acid Inhibitors	1	0	1
0	Cell Elongation Inhibitors	0	1	1
		279	258	537

This table indicates the number of weed species resistant to each site of action. It is important to recognize that many species have developed resistance to multiple sites of action, so the overall total shows unique cases of resistance rather than the number of species.

Climate factors and weed management

Climate factors are critical to the survival of species and weeds are no exception. Climate change factors, including rising temperatures, higher CO₂ levels, and water stress have significant direct and indirect effect on weed biology. These climate change factors affect plant morphological traits, molecular function and physiology developmental processes and in effect, influences availability of nutrients for plants growth and development. Plants experiencing nutrient stress are known to increase root biomass growth and development, which improves the physiological ability of roots to absorb nutrients from deeper soil layers. Also, plants have been observed to increase shoot growth and photosynthetic activities under elevated CO₂ conditions. These factors may allow existing weeds to expand geographical locations or allow weeds to become more problematic (Gray & Brady, 2016; Jugulam et al., 2018; Malarkodi et al., 2017). With the global population anticipated to exceed 9 billion by 2050, climatic uncertainties and potential extremes present inherent environmental risks related to agricultural production and sustainability (Chauhan et al., 2014; Ziska, 2020). Chemical weed management through the use of herbicides has proven to be reliable and economical method of weed control widely used worldwide (Gianessi, 2013; Ziska, 2020). However, there are recent concerns related to herbicide efficacy and climate change effect on susceptibility of weeds to herbicides (Ziska, 2016).

Precipitation and relative humidity on herbicide tolerance

Weather condition before and after application of herbicides is important for herbicide efficacy (Stewart et al., 2012). Precipitation and relative humidity (RH) affect herbicide retention on leaf surface after application of treatment solution (Jugulam et al., 2018). Optimal RH levels during herbicide application enhance herbicide absorption. In conditions of water stress, the effectiveness of herbicides is negatively impacted because of decreased translocation and reduced transpiration rates (Kumar et al., 2023). In an experiment conducted with velvetleaf (*Abutilon theophrasti*), it was observed that glyphosate efficiency in controlling *A. theophrasti* was reduced under drought stress (Zhou et al., 2007). Research indicates that yearly increase in rainfall in arid and semi-arid areas of North America may boost the prevalence of invasive species. As these invasive species gain a stronger foothold, they are expected to change ecosystem processes and properties, many of which interact with factors of global change (Dukes & Mooney, 1999). Green foxtail (*Setaria viridis*) cultivated at temperatures of 22/17 °C has been observed to endure a potentially lethal dose of 100 grams per hectare of glufosinate ammonium at 40 percent RH, achieving 70 percent of the dry weight of the control plants; however, it was destroyed at 95 percent RH (Anderson et al., 1993).

Impact of elevated CO₂ on herbicide tolerance

CO₂ levels have been rising steadily in the past century due to anthropogenic activities and these levels are expected to reach approximately 600 parts per million (ppm) or higher by the end of this century (Cowie et al., 2020; Krajbick, 2023). Increased CO₂ concentration in the atmosphere can result in physiological, anatomical and morphological changes in weeds that can affect the uptake of herbicides, herbicide movement within the plant and herbicide efficacy. These changes, such as variations in leaf thickness, root-to-shoot ratio, and stomatal features, can impact the uptake, translocation, and dilution of herbicides (Ziska, 2020; Ziska et al., 1999). For example, elevated CO₂ in the atmosphere has been found to result in significant stimulation of leaf photosynthesis and plant growth leading to significant reduction in stomatal conductance in lamb's quarters (*Chenopodium album*) (Jugulam et al., 2018; Kumar et al., 2023; Ziska et al., 1999). Observations made in Canada thistle (*Cirsium arvense*) grown at ambient and projected CO₂ levels indicated a notable increase in root to shoot ratios. The research demonstrated that the increase in the root to shoot ratio led to a dilution of glyphosate, allowing the roots of the weeds to survive and reproduce due to decreased herbicide effectiveness (Ziska, 2010, 2016; Ziska et al., 2004).

Temperature effect on herbicide tolerance

Temperature is important for all organisms and has an influence on the establishment of all organisms in every environment. Plants experience changes in temperature on both daily and seasonal scales, and they may be more vulnerable to these temperature variations than many other organisms because they are sessile in nature (Mahan et al., 2004). At the extremes of the temperature range of plants, both low and high temperatures can be lethal as a result of damage to the physical structure of cellular components such as membranes. Herbicide efficacy can be affected by temperature. This occurs due to the altering of uptake of herbicide from the leaf surface, translocation of the herbicide within the plant, and the activation of the

herbicide's metabolism (Mahan et al., 2004). For example, glyphosate was less effective at higher temperatures on *C. canadensis* population as observed by Kleinman et al. (2016). Pot trial experiments involving awnless barnyard grass (*Echinochloa colona*) populations under 20 and 30 °C demonstrated a notable rise in glyphosate resistance levels among resistant populations at 30 °C when compared to 20 °C establishing a reduction in the efficacy of glyphosate at high temperatures (Nguyen et al., 2016). Also, researchers have observed a reduction in the sensitivity of *C. canadensis* and *C. album* populations to glyphosate when exposed to high temperatures and increased levels of CO₂ (Matzrafi, 2019). These findings highlight the combined influence of various climatic variables on herbicide efficacy.

CONCLUSIONS

The issue of climate change though a polarizing political issue, cannot be ignored given the existential threat that it represents and the wide spread impact on agriculture and food security. Climate change is anticipated to influence weeds by increasing their tolerance to herbicides due to significant changes in weed physiology affecting absorption and translocation within the plants. This scenario is a major concern and requires extensive research for more sustainable and integrated approach to minimize the risks of weeds. Special attention must be paid to the careful use of herbicides in weed management. The time of application, wind direction, precipitation, temperature and humidity should be taken into account when using herbicides to obtain optimal results. This is vital in order to reduce the development of resistant weed biotypes.

ACKNOWLEDGEMENTS

This review was conducted with support from Tempus Public Foundation and the Ghana Scholarship Secretariat.

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